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14. ABSTRACT Space collision avoidance requires more international cooperation in order to move beyond catalog maintenance toward active space traffic management. Spacecraft and sensor owners should seek out ways to provide information to each other for collectively improved orbital safety. In addition to increasing space traffic, recent collisions in space have produced debris that will remain hazardous to navigation for over one hundred years. While technical proposals for sharing data exist, psychological factors, such as power, fear, trust, and protection of intellectual capital, are the keys to improvement. Decision-makers should consider ten recommended actions that would improve space collision avoidance for all, including themselves.					
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JOINT ADVANCED WARFIGHTING SCHOOL**

**FLYING BLIND AT OVER 7 KILOMETERS PER SECOND:
A CONCEPT FOR IMPROVING SPACE COLLISION AVOIDANCE**

by

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A paper submitted to the Faculty of the Joint Advanced Warfighting School in partial satisfaction of the requirements of a Master of Science Degree in Joint Campaign Planning and Strategy. The contents of this paper reflect my personal views and are not necessarily endorsed by the Joint Forces Staff College or the Department of Defense.

This paper is entirely my own work except as documented in footnotes.

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20 May 2010

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ABSTRACT

All spacecraft and sensor owner/operators should find ways to overcome technical and psychological factors currently preventing them from sharing position data and velocity vectors, improving collision avoidance in order to preserve collective access to the global commons of space. The following pages capture one promising path towards improving collision avoidance collectively for all space operators. This path specifically focuses on the crowded orbits circling near Earth's poles, since those orbits' great utility makes them the desirable choice for so many operators.

Chapter 1 describes the 2009 Iridium-Cosmos collision in detail, while Chapter 2 provides a description of the four key components of collision avoidance planning. Chapters 3 and 4 explore the current obstacles preventing better collision avoidance, separating them into technical and psychological categories and addressing ways to overcome each obstacle. Cooperation, even with a real or perceived enemy/competitor, is essential to continued success in space. The conclusion ends with 10 recommendations that decision-makers around the world should consider in order to minimize the risk of collision for all spacecraft, including their own. Appendix A lists the 10 recommendations.

Current separation on Earth has already contributed to one collision in space – more collisions should not be necessary to convince decision-makers that the fear of collision should overcome the fear of each other at this point. Collisions in space decrease everyone's access to the global commons of space, therefore, the space community should draw closer on Earth in order to achieve safer separation in space.

For my son, Richard

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INTRODUCTION

“... the seminal event in this past year ..., I would have to say it was the Cosmos-Iridium collision. The big space theory, like the big sky theory, kind of came to a close when that happened.”

—General Kevin P. Chilton, CDR USSTRATCOM¹

Space has gotten crowded, especially in low Earth orbits around the poles.² As more and more countries and private organizations have gained access to space, the sheer volume of traffic has increased the risk of collision significantly.³ There are many reasons for concern with this risk. Not only is it expensive to launch and operate a satellite in space, but people around the world have become dependent on data from spacecraft. Any disruption of this continuous flow of data can damage corporate, national, scientific and even individual livelihoods here on earth. Corporations depend on space for communication. Nations depend on space for intelligence gathering and other vital functions. Scientists depend on space for experimentation and observation. Many individuals rely on space for navigation. Product delivery from space has become

¹ General Chilton is a former astronaut with three Shuttle missions and the current commander of United States Strategic Command. Kevin P. Chilton, “Commander’s Perspective” (Speech, Strategic Space Symposium, 3 Nov 09, http://www.stratcom.mil/speeches/26/2009_Strategic_Space_Symposium_Commander039s_Perspective) (accessed May 19, 2010).

² In 2007, two years before the collision between Iridium-33 and Cosmos-2251, John Campbell, Iridium’s Vice President for Government Affairs, spoke about Iridium spacecraft operations, describing the complex environment and Iridium’s policies. John Campbell, et al. "Forum on National Security Space: Examining Codes and Rules for Space" (Text from George C. Marshall Institute’s Washington Roundtable on Science and Public Policy, June 27, 2007), 7 <http://www.marshall.org/pdf/materials/554.pdf> (accessed May 19, 2010).

³ Over 60 nations operate over 1100 spacecraft among 20,000 pieces of debris currently, according to DepSecDef Lynn, speaking at the National Space Symposium on 14 Apr 10, page 2 <http://www.defense.gov/speeches/speech.aspx?speechid=1448> (accessed May 19, 2010).

ubiquitous, invisibly influencing billions of people around the world directly and indirectly in ways that only become visible when delivery of the product suddenly stops.

Collisions in space have short-term and long-term negative effects that reach across the entire space community and should serve as motivation for all to improve current processes to avoid future collisions. Current efforts to establish international space “rules of the road” are part of the space collision-avoidance solution, but these efforts fail to address the foundational aspects affecting poor space situational awareness. Just as timed lights guide automobile traffic through busy intersections safely, technical means of improving space situational awareness are possible given the application of time and money. However, psychological factors also play a role.

In that regard, space travel is similar to traveling by car. During a daily commute, each driver not only chooses whether to obey all traffic laws equally, but also chooses whether to drive aggressively, risking collision for a perceived benefit, or drive defensively, avoiding collision with safety as its own benefit. These choices, these individual calculations of risk and reward, reflect the psychological motivations of each driver. Unfortunately, driving one’s car is not a closed system – one driver’s miscalculation can affect the commute of many other drivers.

Space activity also involves psychological factors and individual choice, including decisions to enhance national prestige, assume risk, assuage fears, and compete as part of human existence. When these psychological factors unintentionally impinge upon safety, the results impact the collective space community, which must address these issues in order to prosper. All spacecraft and sensor owner/operators should find ways to overcome technical and psychological factors currently preventing them from sharing

position data and velocity vectors, with the result of improving collision avoidance in order to preserve collective access to the global commons of space.

On 10 February 2009, the first “t-bone” collision between two spacecraft occurred when both attempted to cross a busy “intersection” around 790 km above the Earth near the North Pole at the same time.⁴ At 11:56 a.m. Eastern Standard Time that day, Iridium-33 and Cosmos-2251 collided at an approximately 100-degree offset angle with a closing speed near 10 km/sec. The results were catastrophic.



Figure 1. Polar Orbit Collision on 10 Feb 09⁵

⁴ Dr T.S. Kelso is a senior research astrodynamist for the private Center for Space Standards & Innovation (CSSI) in Colorado Springs. A retired US Air Force Colonel, Dr Kelso worked on the USAF Chief of Staff's future studies SPACECAST 2020 and Air Force 2025, and he led Department of Defense support to the Shuttle Columbia Accident Investigation Board. He has been a part of the space surveillance community for over 20 years. He provided a detailed analysis of the Iridium-Cosmos collision at the 2009 Air Force Maui Optical Site conference. T.S. Kelso, “Analysis of the Iridium 33-Cosmos 2251 Collision” (Presentation at 2009 AMOS Conference, <http://www.centerforspace.com/downloads/files/pubs/AMOS2009.pdf>), (accessed May 19, 2010), 1.

⁵ Analytic Graphics, Inc. (AGI) “Iridium 33 and Cosmos 2251 Satellite Collision.” (AGI Web site. Windows Media Player video file, available from <http://www.agi.com/corporate/mediaCenter/news/iridium-cosmos/>, (accessed September 10, 2009).

The aftermath of this collision will occupy the minds of space professionals for years. Like all objects in polar orbits, both spacecraft were moving from pole to pole roughly every 45 minutes, travelling at speeds of over 7 km/sec (over 25,000 kph). This high-speed collision destroyed both spacecraft, creating over 1300 debris fragments large enough to track and an unknown number of smaller fragments.⁶ Each fragment now occupies an uncontrolled polar orbit of its own, shooting through one of the busy “intersections” at the North and South Poles roughly every 45 minutes with enough kinetic energy to destroy or severely damage any spacecraft in its way. Fragments continually cross these polar “intersections” at various times and altitudes from different directions. Perhaps most significantly, the parameters for each fragment change slightly and unpredictably over time, creating a collision avoidance nightmare.

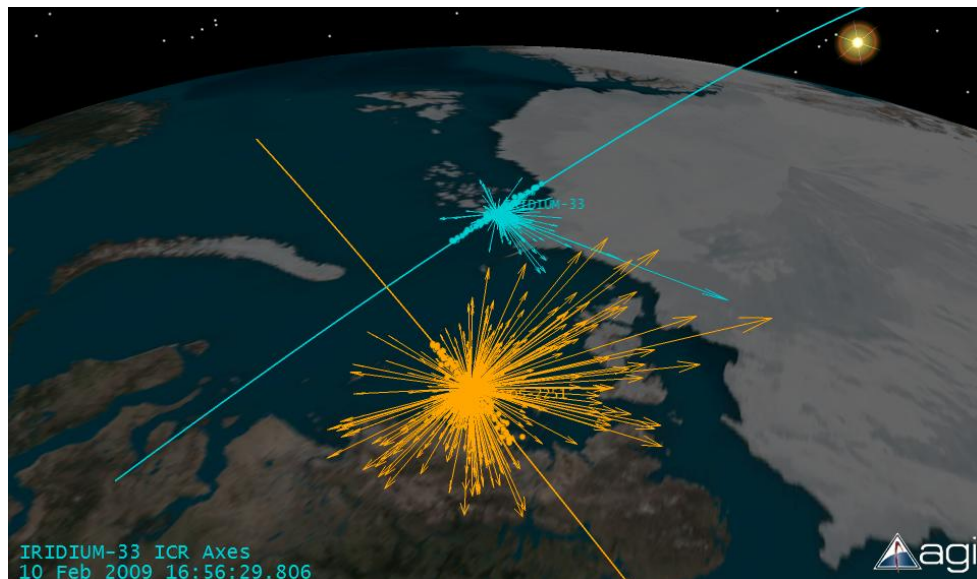


Figure 2. Debris relative velocity pattern based on tracked fragments⁷

⁶ T.S. Kelso, “Analysis of the Iridium 33-Cosmos 2251 Collision,” 4.

⁷ T.S. Kelso, “Analysis of the Iridium 33-Cosmos 2251 Collision,” 6.

Understandably, every spacecraft owner/operator using polar orbits remains concerned about the probability of their spacecraft catastrophically meeting any one of those many fragments. For smaller organizations that have only one spacecraft in polar orbit, a single fragment in an unpredicted place could irreparably harm their spacecraft and put them out of business.

NASCAR Analogy for Orbital Traffic Patterns

A common analogy to explain geostationary orbits is to envision a person standing at the center of a racetrack facing a racecar. The person turns slowly at a speed proportional to the speed of the racecar going around the track, making the racecar appear to remain centered in their field of view. In translation to orbit descriptions, operators place spacecraft in geostationary orbits at roughly 36,000 km above the equator, the altitude block where orbital speeds proportionally match the speed of Earth's rotation. When perfectly matched, this orbit selection makes a spacecraft appear to remain centered over a point on the equator.⁸

Racing also can provide a reasonable visualization of traffic patterns in polar orbits, with a few significant adaptations. Imagine a racetrack like the Daytona International Speedway, where the banked walls allow cars to reach speeds around 200 mph. For NASCAR, each car has a team of people supporting every move made on the track. Spotters play an important role, providing their drivers with warning of hazards the

⁸ Any racecar analogy is limited to visualizing orbital traffic patterns only, since spacecraft leverage gravity to “power” sustained motion. In contrast, racecars will stop without continuous engine power. For an excellent description of basic orbital mechanics, see Jim Oberg, *Space Power Theory*, (Colorado Springs, CO: Government Printing Office, 1999), Appendix 1 to Chapter 1.

drivers cannot see. For example, a driver making a pass relies heavily on the spotter to confirm when it is safe to move in front of a car he just passed.

NASCAR officials and fans have seen many wrecks result when a spotter mistakenly calls a pass complete 1 inch too soon. The driver, unaware of the spotter's mistake, attempts to move in front of the car he just passed, creating a multi-car pileup when one inch of his car's tail connects sideways with one inch of the other car's nose at 200 mph. The spotter feels terrible, the driver feels betrayed by the spotter, and the team's race day may be over, along with all the other teams with cars caught up in the wreck. Race officials have to slow or stop the race for clean-up crews to remove the debris and allow the remaining cars to resume racing. Team owners with cars involved in the initial or follow-on collisions may be out millions of dollars, especially if the wreck affects the team's participation in future races. These costly wrecks happen on oval super-speedway racetracks all across the United States. As the Iridium-Cosmos collision demonstrates, they can happen in space as well.

Applying the racing analogy to polar orbit traffic patterns requires several adjustments. While geostationary orbits involve spacecraft moving in the same general direction at the same general speed – like a standard NASCAR race on an oval track – polar orbits add many additional challenges. For the analogy to hold in polar orbits, the speed of the cars must increase from 200 mph to 500 mph, since orbits closer to the Earth require orbital speeds of 7 to 8 km/sec compared to 3 km/sec in geostationary orbits.⁹ Additionally, the polar orbit analogy would use a half-mile track instead of Daytona's 2.5

⁹ National Research Council, *Orbital Debris: A Technical Assessment* (Washington DC: National Academy Press, 1995), 89.

miles, since the distance around the Earth is much shorter closer to the Earth. Sustaining 500 mph speeds on a half-mile track will require near-vertical banking in the turns. Since slower speeds in the turns cannot produce sufficient centrifugal force to complete each near-vertical turn, the short distances between turns will not allow stopping for any reason, much like a spacecraft changing speed in a given orbit will cause it to leave that orbit. Finally, getting cars up to speed in the first place requires rocket engines similar to the rockets used to propel spacecraft to orbital speeds.

Besides track modifications, the racecars in this analogy need modification in order to be more like spacecraft. The windshield is painted black, leaving the side windows clear to allow small adjustments relative to cars in the immediate vicinity, much like docking with the space station. To make up for the lost situational awareness, each team is allowed to have as many spotters as the owner can afford, but this requires significant discipline on the radio to allow the right spotter to make the right call at the right time. The spotters represent sensor operators with the capability to provide data regarding spacecraft passing through their sensor's field of view. Reflecting the ongoing nature of space operations, racecars in this analogy may enter the race at any time. Since a spacecraft produces results with each "lap" around Earth without regard to the activities of other spacecraft, this hypothetical race never ends, and each owner earns millions of dollars based on the number of completed laps.

One final track modification is necessary to illustrate the complexity of polar orbits – change the layout from oval to a figure 8. This modification captures the challenges of the "intersections" at the North and South Poles that each spacecraft must pass through every 45 minutes. On this hypothetical racetrack, depending on the angle

at the intersection, closing speeds between approaching cars could reach 1000 mph, making each collision at the intersection fatal. In this analogy, however, no one can stop traffic to allow track crews to clean up the debris; spotters must simply do their best to guide their drivers to avoid the remains every time they pass through the intersection. Replacing the driver with a remote control option would make driving safe for humans, but would add delays for commands to reach the car and increase potential error due to the possible disorientation of a remote operator not experiencing all the forces at work in the car at any given time. Given all of these dangers, one must question why more cars (spacecraft) join the race every year. Like spacecraft going into polar orbit, more and more cars enter this hypothetical racetrack each year because of the high monetary reward paid to owners for each completed lap. In essence, as long as income exceeds expenses, the business model works regardless of short-term risk or long-term damage to the viability (trafficability) of polar orbits. As a case in point, consider that even after the Iridium-Cosmos collision, Iridium ended 2009 with a 20% increase in its ability to produce income, fueling Iridium's next-generation satellite program and enhancing its short-term profitability.¹⁰

Clearly, the risk for collision on our hypothetical racetrack is extremely high. However, ending the race is not an option because every lap around our racetrack is important. Spacecraft in polar orbit are responsible for how the world gathers information, communicates, predicts its weather, and much more. Given the ever-

¹⁰ Iridium's Earnings before Interest, Taxes, Depreciation, and Amortization (EBITDA) increased to over \$133 million for 2009. Investors use EBITDA to compare companies with differing debt structure or tax situations. Iridium numbers at: <http://investor.iridium.com/releasedetail.cfm?ReleaseID=452220> (accessed May 19, 2010)

increasing use of space, there must be a way to make navigating this space “racetrack” a less risky enterprise.

Considering the dire consequences of collisions on the space community, one would expect its members to develop procedures to prevent another Iridium-Cosmos collision. Any such procedures must be technically feasible and be supported by the collective commitment of space-faring nations and organizations. While sharing positional and vector data is easy in theory, in reality any viable solution requires technical work backed by strong organizational commitment. Of these two challenges, the technical problem is easier to solve. Achieving organizational commitment is much harder. Papers already exist outlining an initial draft of the technical requirements for an international civil space situational awareness concept, acknowledging the need for organizational commitment to proceed. The United Nations has issued various documents regarding space debris for many years, yet actual progress is limited.

After the collision, leaders of some organizations, including Iridium, have made recent statements indicating their willingness to share their own positional and vector data in an effort to improve collective safety. Others, however, seem much less willing. In a recent statement regarding China’s anti-satellite program, the Scientific Advisor to India’s Defence Minister asserted that India needed to develop its own ability to “track the movement of enemy satellites before making a kinetic kill.”¹¹ From this statement, one can surmise that India’s leaders are not interested in sharing information about Indian spacecraft with China’s leaders due to Indian fears that the information would simplify

¹¹ *Asia Defence News*, Apr 15-May 14, 2010 edition, 14-15

Chinese anti-satellite targeting efforts. This nation-state example of fear also applies to corporate leaders and their concern over vulnerabilities of their assets to other corporations. Thus, the toughest obstacle blocking improvement to space collision avoidance is convincing each decision-maker across the space community that cooperation is in his or her own best interest.

This thesis offers a potential breakthrough by directly addressing the underlying psychological factors that currently prevent further technical progress. This approach seeks to unite the disparate efforts of technical and political experts working separately and perhaps at cross-purposes. After addressing the underlying psychological issues identified in this thesis, the collective space community should be prepared to unite to move international technical capability beyond passive catalog maintenance toward active and effective collision avoidance. Without unified action, additional collisions will happen over time, eventually closing access to critical orbits that are currently vital to many economic, political, scientific, and military goals. Decision-makers should consider acting on 10 recommendations in order to secure their own continued success.

CHAPTER 1

Collision

“We grit our teeth and hold our breath – that’s our action.”

—John Campbell, Iridium Vice President¹

At 11:56 a.m. Eastern Standard Time on 10 February 2009, Iridium Satellite LLC spacecraft operators lost contact with the Iridium-33 spacecraft. Iridium-33 had collided with another spacecraft, later determined to be Cosmos-2251, a derelict Russian spacecraft. This chapter examines how these two satellites came to be in the same place at the same time and the lasting results from their collision. Both satellites

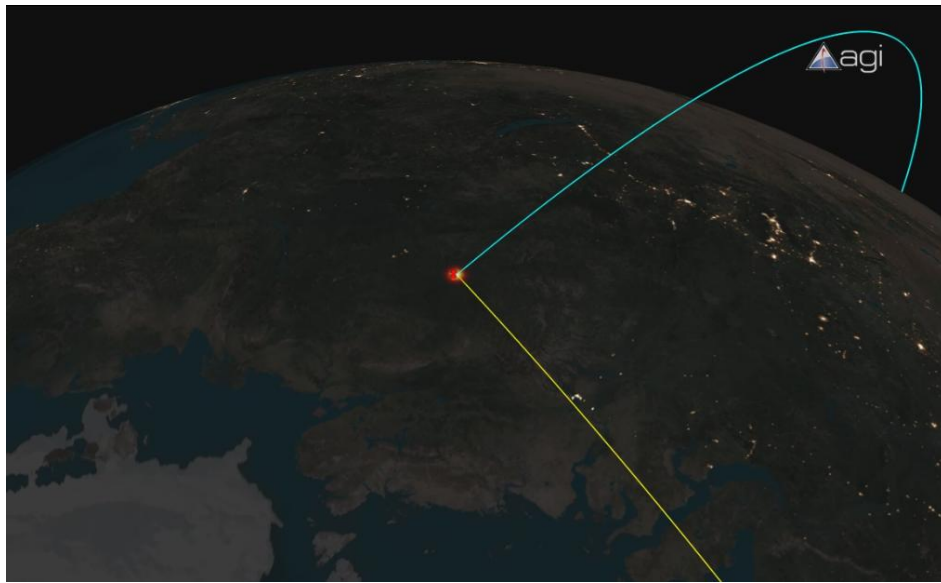


Figure 3. Collision on 10 Feb 09²

¹ John Campbell describing Iridium’s collision avoidance procedures. John Campbell, et al. "Forum on National Security Space: Examining Codes and Rules for Space" (Text from George C. Marshall Institute’s Washington Roundtable on Science and Public Policy, June 27, 2007), 9 <http://www.marshall.org/pdf/materials/554.pdf> (accessed May 19, 2010).

² Analytic Graphics, Inc. (AGI) “Iridium 33 and Cosmos 2251 Satellite Collision.” (AGI Web site. Windows Media Player video file, available from <http://www.agi.com/corporate/mediaCenter/news/iridium-cosmos/>, (accessed September 10, 2009)

involved in the collision operated in the most crowded area of space – polar orbits. Unlike other orbits, each spacecraft in a polar orbit will pass over the entire globe over time. [Envision wrapping a continuous string around a ball, only crossing or touching other strands at the top and bottom of the ball.] As a result, operators from many government, civilian, scientific, and commercial organizations around the world depend on continued availability of clear paths around the poles. Each organization attempts to select the optimal balance between the best orbit to accomplish its mission and the projected available safe orbits. Varied altitudes, inclinations, and right ascensions have allowed hundreds of spacecraft to use polar orbits.³ Indeed, two companies, Iridium and OrbComm, together operate more than 100 satellites in polar orbits.⁴

History and Context

In 1993, Russia launched the Cosmos-2251 spacecraft, a Strela-2M military communications satellite designed to provide encrypted communication capability for Russian theater forces.⁵ The Russian government reported that it had stopped functioning

³ Inclination refers to an orbit's "tilt" from the equator; polar orbits have inclinations near 90°. Right ascension refers to the "swivel" of an orbital plane, measured from the vernal equinox eastward along the equator to the point where the spacecraft "ascends" across the equator from south to north. Variations in these two orbital elements as well as altitude provide many orbit choices, but intersections occur that require one of the spacecraft to maneuver, changing orbits sufficiently to avoid a collision.

⁴ Iridium has 74 remaining spacecraft; OrbComm has 36. T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," 7.

⁵ Strela-2M spacecraft details at: <http://www.astronautix.com/craft/strela2m.htm> (accessed May 19, 2010).

two years later, many years before the collision.⁶ Since the spacecraft was no longer maneuverable, owners and operators of other spacecraft simply had to avoid it. The spacecraft's relatively large size and proximity to Earth allowed many sensor operators around the world the opportunity to monitor its location. Periodic sensor observations indicated that the spacecraft was gradually losing altitude at a reasonably predictable rate, allowing others to plan and execute occasional collision avoidance maneuvers based on their risk tolerance regarding the degree of uncertainty at any given time.

Four years after the launch of Cosmos-2251, the Iridium Satellite LLC launched seven spacecraft from Baikonur Cosmodrome in Russia. These seven spacecraft, including Iridium-33, fanned out into one of the six orbital planes in Iridium's constellation of 66 operational spacecraft and 9 spares. Iridium separated its spacecraft along these polar orbits in order to provide worldwide voice and data communication via hand-held satellite phones, and its spacecraft crisscross the poles amid the traffic of hundreds of other military and commercial spacecraft.⁷

Since the same operators control each of the 75 spacecraft, potential collisions between Iridium spacecraft are the easiest to predict and avoid, since the operators know the position of each of their own spacecraft, unlike the thousands of other objects in intersecting polar orbits. Figure 4 displays the Iridium spacecraft in their assigned planes on the day of the collision. Note the polar intersections between planes.

⁶ Russian comments in the *Moscow Times* at: <http://www.themoscowtimes.com/news/article/first-satellite-collision-called-threat-in-space/374510.html> (accessed May 19, 2010).

⁷ Information about current Iridium constellation and services at: <http://www.iridium.com/About/CompanyProfile/GlobalNetwork.aspx> (accessed May 19, 2010).

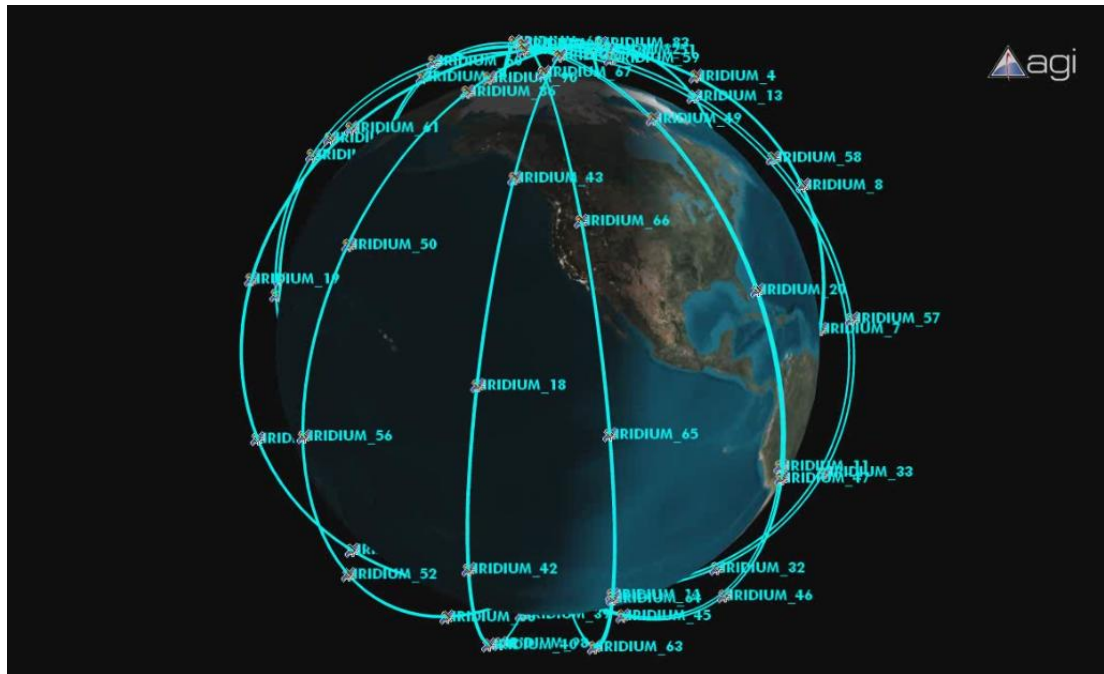


Figure 4. Iridium constellation on 10 Feb 09⁸

Prior to the collision, Iridium planners were aware of the possibility of Iridium-33 colliding with Cosmos-2251, relying on orbit predictions generated from earlier sensor observations of the Russian spacecraft as they had done many times before.⁹ While these planners could be relatively sure of the positions of each of their own spacecraft, third-party sensor observations provided their only insight into the locations of other spacecraft and debris in orbit. Additionally, at the time of the collision, Iridium had 75 spacecraft on orbit, 66 operational satellites and 9 on-orbit spares.¹⁰ Iridium's planners were not

⁸ Analytic Graphics, Inc. (AGI) "Iridium 33 and Cosmos 2251 Satellite Collision." (AGI Web site. Windows Media Player video file, available from <http://www.agi.com/corporate/mediaCenter/news/iridium-cosmos/>, (accessed September 10, 2009).

⁹ T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," 2.

¹⁰ John Campbell, et al. "Forum on National Security Space," 6.

only worried about external dangers; they were also concerned with maintaining optimized separation between their own spacecraft in order to provide their customers with the best possible service.¹¹ With responsibility for so many spacecraft in a highly congested orbital regime, Iridium's planners sorted through over 1,000 predictions per week of close approaches (within 5 km) to one of their spacecraft.¹² In a prediction released less than 2 hours before the collision, Iridium-33 and Cosmos-2251 appeared to miss each other by 584 meters – other Iridium spacecraft had much closer approaches listed in the same prediction.¹³ Iridium's policy of ignoring the uncertainties inherent in the prediction source material had worked thousands of times before.¹⁴ Unfortunately, each prediction is like a coin toss – the coin has no memory and neither does a prediction. The probabilities are not cumulative; they are fresh each time. Like a person expecting a coin to come up tails after three consecutive heads, it is still equally possible the coin will come up heads again. The events of 10 Feb 09 proved that collision predictions are not cumulative either.

The actual results of this collision extend far beyond the momentary minor degradation of communication in Iridium's constellation. With both spacecraft moving at the extremely high speeds (over 7 kilometers per second) required to maintain orbit, their roughly perpendicular paths met catastrophically at a location approximately 790 kilometers over Siberia with a closing velocity of over 10 kilometers per second (over

¹¹ John Campbell, et al. "Forum on National Security Space," 7.

¹² T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," 3.

¹³ Ibid., 2.

¹⁴ John Campbell, et al. "Forum on National Security Space," 9.

36,000 kilometers per hour). Figure 5 shows how the debris from both destroyed spacecraft began to spread out immediately, creating rings along their previous orbits within 24 hours. By August 2009, six months later, the debris field had spread out laterally, now crisscrossing the poles in many directions at various altitudes at any given time. Previous fragments from single objects have spread into a shell around the Earth within two years.¹⁵ Figure 6 depicts the orange and blue fragments moving across the North Pole in comparison to the orbits of just the Iridium constellation. Iridium's original six orbital planes are less distinctly visible, partly due to unique collision avoidance maneuvers for each spacecraft relative to other objects, including the depicted debris. Figure 7 shows active polar spacecraft in sun-synchronous orbits only, without the debris from Figure 6 and without spacecraft in other polar orbits that also cross the poles in the same area. Collectively, Figures 6 and 7 provide some insight into the collision avoidance challenges for polar orbits that were hard enough before for just one type of polar orbit (Figure 7). Those challenges are even harder now with the added debris (Figure 6).

¹⁵ For example, the Ariane-1 H10 upper stage that exploded on 13 Nov 86 had spread to cover almost all longitudes by Apr 88. F. Kenneth Chan, *Spacecraft Collision Probability* (El Segundo, CA: The Aerospace Press), 218-219.

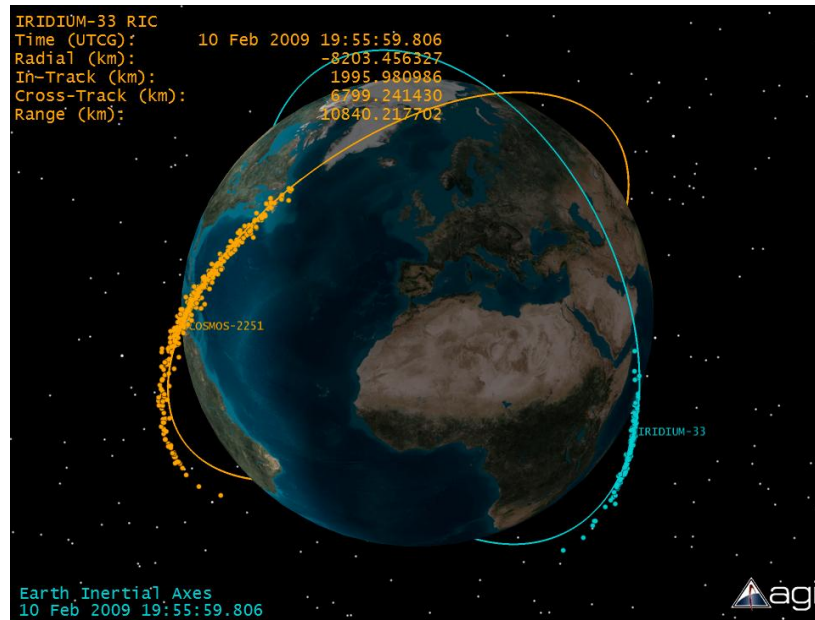


Figure 5. Debris patterns 180 minutes after collision¹⁶

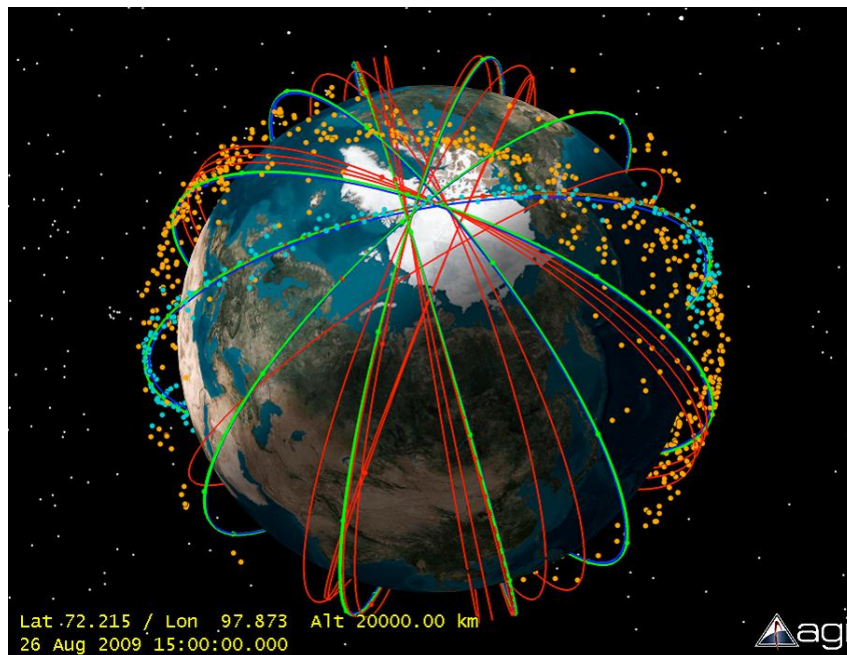


Figure 6. Debris pattern and Iridium constellation orbits on 26 Aug 09¹⁷

¹⁶ T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," 5.

¹⁷ Ibid., 1.

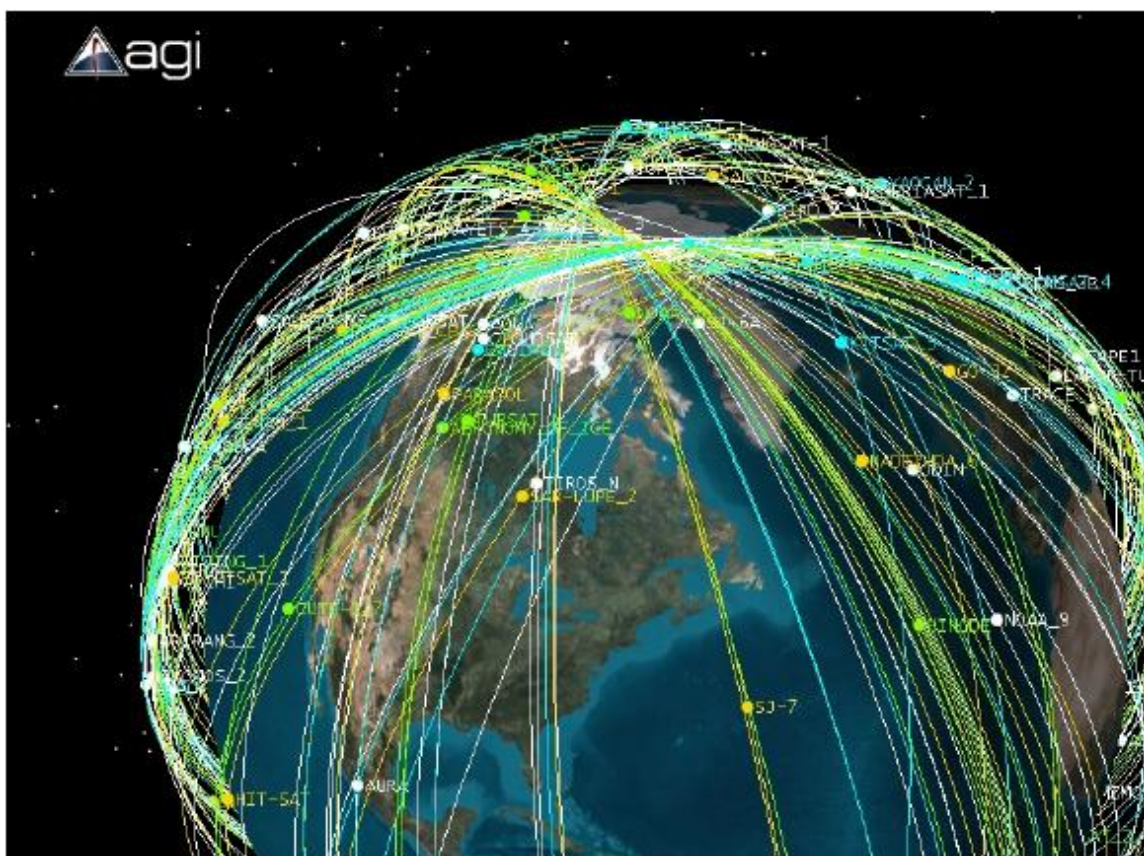


Figure 7. Active Spacecraft in Polar, Sun-Synchronous Orbits¹⁸

Since even tiny paint flecks can cause serious damage at orbital speeds, each of these fragments pose a significant hazard for any vehicle. During the STS-7 mission in June 1983, the Shuttle Challenger experienced the first loss of a spacecraft part directly attributable to human-made orbital debris, but not the last. During the mission, the Shuttle crew reported an impact crater on the outer pane of one of the orbiter's windows, seen in Figure 8. This outer windowpane was 5/8 inch thick and built to withstand pressures of 8600 pounds per square inch and temperatures up to 482°C. From trace material

¹⁸ Ray Williamson, Ben Baseley-Walker, and Brian Weeden. "Space Traffic Management." (Presented to the Space Generation Advisory Council on 2007 International Space University team project, July 31, 2008) slide 27.

remaining in the crater, NASA determined that the damage came from a white paint speck about 0.2 millimeters in diameter traveling between 3 and 5 km/sec. NASA had to replace the window prior to Challenger's next mission two months later.¹⁹

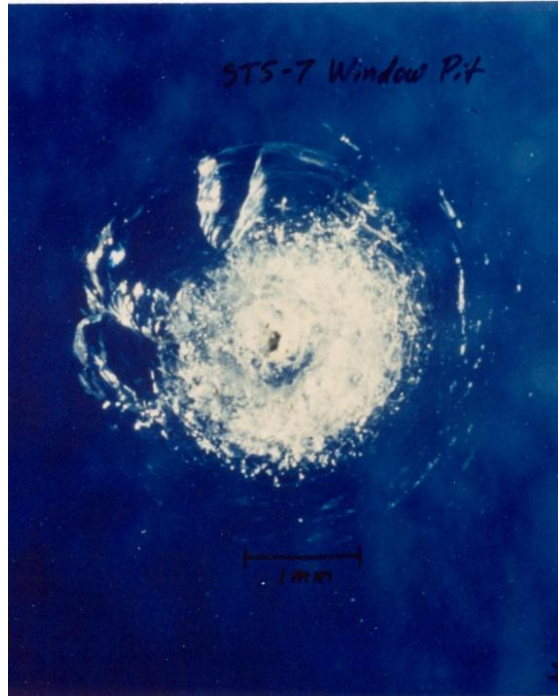


Figure 8. Paint fleck impact on Shuttle window²⁰

During the STS-94 mission in 1997, Shuttle Columbia sustained damage to a window resulting from a collision with an aluminum oxide particle roughly 150 microns in size – approximately 0.006 inches, or the size of a piece of dust.²¹ Since standard solid rocket exhaust contains tiny particles of aluminum oxide dust, the impacting particle probably came from some unknown solid rocket motor firing at some unknown time

¹⁹ From an instructional lesson plan regarding the incident. Available at: <http://illuminations.nctm.org/LessonDetail.aspx?ID=L376> (accessed May 19, 2010).

²⁰ NASA photo available at: <http://www.orbitaldebris.jsc.nasa.gov/photogallery/photogallery.html> (accessed May 19, 2010).

²¹ 1 micron = 1,000,000 of a meter (roughly 0.00004 inches)

prior to the STS-94 mission.²² NASA had to replace Columbia's window prior to its next mission four months later.²³ Debris particles have increased to the point that NASA routinely replaces one or two windows per Shuttle mission.²⁴ Shuttles return to Earth within days of launch, but a typical spacecraft in low Earth orbit for 10 years can expect between 100 and 1000 impacts from small particles.²⁵



Figure 9. Aluminum oxide particle impact on Shuttle window²⁶

²² National Research Council, *Orbital Debris: A Technical Assessment* (Washington DC: National Academy Press, 1995), 24.

²³ Hypervelocity Impact Test Facility information available at: <http://hitf.jsc.nasa.gov/hitfpub/problem/actualimpact-sts94-window.html> (accessed May 19, 2010).

²⁴ NASA Debris Handbook, pg 23. Available at: <http://www.hq.nasa.gov/office/codeq/doctree/NHBK871914.pdf> (accessed May 19, 2010).

²⁵ National Research Council, *Orbital Debris*, 81.

²⁶ Hypervelocity Impact Test Facility photo. Available at: <http://hitf.jsc.nasa.gov/hitfpub/problem/actualimpact-sts94-window.html> (accessed May 19, 2010).

Spacecraft have collided with larger pieces of debris as well. In 1996, a French spacecraft in polar orbit, the Characterisation de l'Environnement Radio-electrique par un Instrument Spatial Embarqué (CERISE), lost part of its gravity gradient boom to a piece of Ariane rocket body debris.²⁷ Since the boom was part of its designed method to maintain orientation, the spacecraft began to tumble. Upon reviewing sensor information to assess what had happened, CERISE operators reprogrammed the spacecraft to be able to maintain orientation without the complete 6-meter boom and it recovered from its tumble.²⁸

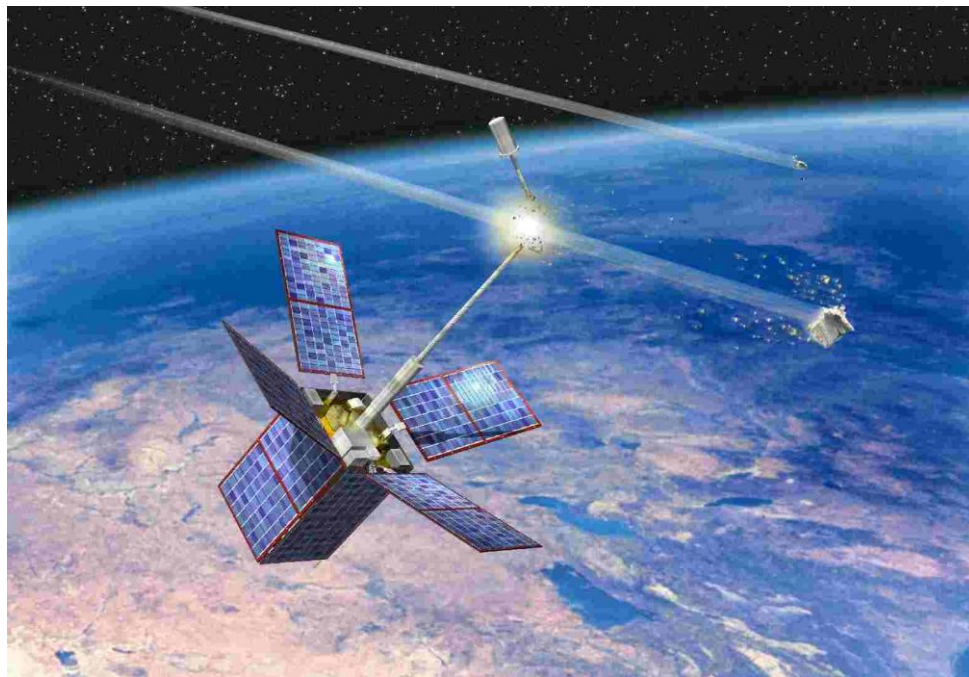


Figure 10. CERISE spacecraft collision with Ariane rocket body debris, 1996²⁹

²⁷ http://www.tbs-satellite.com/tse/online/sat_cerise.html (accessed May 19, 2010).

²⁸ Details of the incident and the crew's recovery actions available at: <http://sat-index.co.uk/failures/index.html?http://sat-index.co.uk/failures/cerise.html> (accessed May 19, 2010).

²⁹ Image from French space agency, Centre National d'Etudes Spatiales (CNES). Available at: http://debris-spatiaux.cnes.fr/english/index_eng.html (accessed May 19, 2010).

If the impact hits a critical component, even small particles can affect a spacecraft's mission; but a piece of debris with 1 kg³⁰ of mass moving at 10 km/sec can destroy a 1000-kg spacecraft.³¹ Iridium-33 weighed roughly 690 kg; Cosmos-2251 weighed roughly 900 kg. Their closing speed was near 10 km/sec. Hundreds of pieces of debris from the Iridium-Cosmos collision are large, some measuring in feet with significant, but unknown mass, and all are moving at orbital velocities measured in km/sec. A few pieces of debris from this collision have already reached the 300km-600km altitudes currently used for manned spaceflight, creating additional hazards to future missions.³² Table 1 shows a correlation between debris size and expected damage.

Debris size	Characteristics
< 0.01cm	Erosion of surfaces
0.01 to 1 cm	Significant damage Perforations Consequences vary depending on equipment affected
1 to 10 cm	Very significant damage
> 10 cm ³³	Catastrophic consequences for a satellite

Table 1. Correlation between debris size and expected damage.³⁴

³⁰ Approximately 2 pounds

³¹ National Research Council, *Orbital Debris* 4.

³² Space Shuttle altitude range is in the table on page 9 of the UN Report on Space Debris, 1999. Available at: http://www.orbitaldebris.jsc.nasa.gov/library/UN_Report_on_Space_Debris99.pdf (accessed May 19, 2010).

³³ Larger than approximately 4 inches

³⁴ Table from French space agency, Centre National d'Etudes Spatiales (CNES). Available at: http://debris-spatiaux.cnes.fr/english/index_eng.html (accessed May 19, 2010).

These hazards will exist for a long time. Figures 11 and 12 illustrate that many of these fragments will remain in orbit for over 100 years, gradually descending until burning into the atmosphere. Each red dot in the figures represents a trackable fragment created when these two satellites collided, confirming at first glance that there are now many more objects for other spacecraft to avoid. Perigee Altitude for a given fragment refers to the altitude when it is closest to Earth. Apogee Altitude refers to the altitude when it is farthest away from Earth. Together, these two numbers describe key elements of each fragment's orbital path. The L-shaped clustering of fragments at 790 km on each axis reflects expected distribution based on the collision altitude. The contour lines in each figure reflect a mathematical equation that uses apogee and perigee to calculate how long it will take each unpowered fragment to spiral into the Earth's atmosphere. In each figure, many fragments are above the 100-year contour line, representing a navigation hazard to orbiting spacecraft well into the next century.

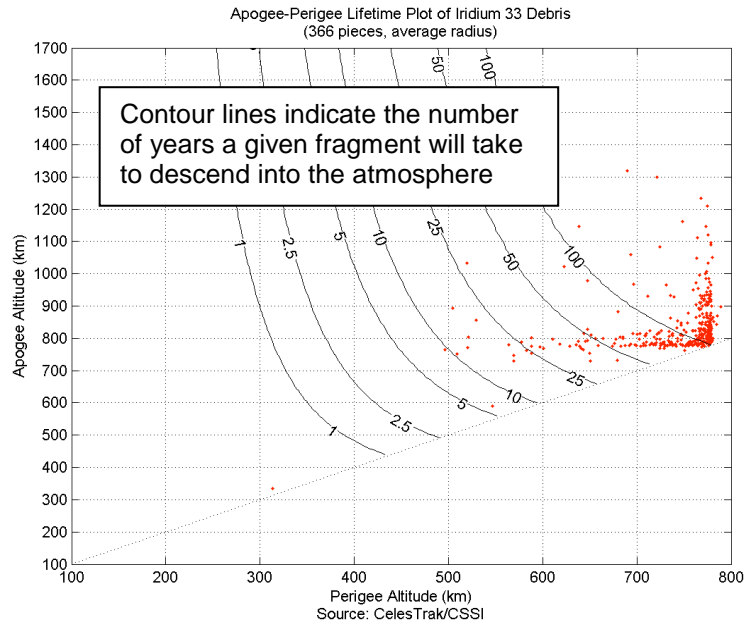


Figure 11. Debris lifetime for Iridium-33 fragments³⁵

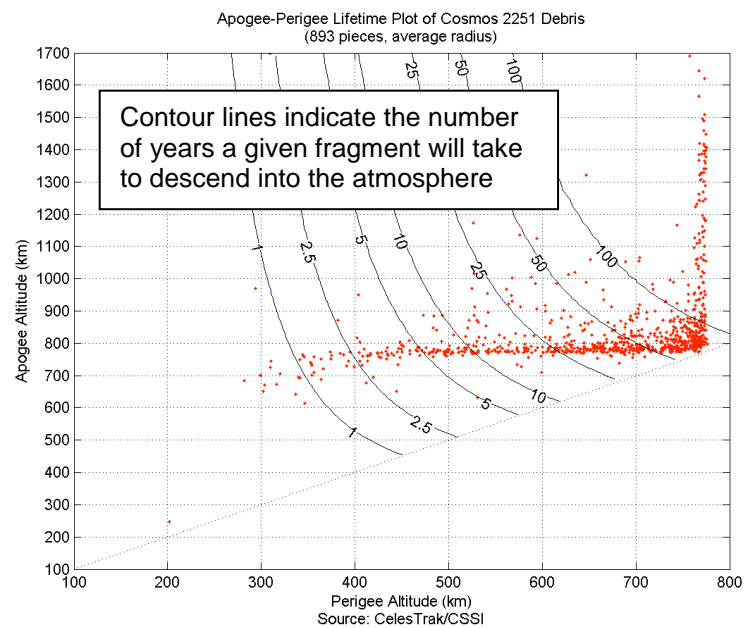


Figure 12. Debris lifetime for Cosmos-2251 fragments³⁶

³⁵ T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," 7.

³⁶ Ibid., 8.

After this collision, NASA calculated an immediate 6% increase to 1 in 318 for the odds of impact for the International Space Station, currently orbiting at approximately 350 km, over 400 km below the altitude of the collision.³⁷ As more fragments descend, these odds will get worse until NASA disposes of the International Space Station – 2011 budget additions will extend station operations funding from 2016 to 2020.³⁸ This is the danger posed by just the initial collision. The dangers multiply as the current trackable fragments eventually begin to collide with each other.

Cascading collisions, often labeled “the Kessler Syndrome,” could reduce the sizes of future fragments until all become too small to track. The term “Kessler Syndrome” refers to Don Kessler, who famously authored a 1978 report documenting and projecting debris production rates based on space practices at the time. As a result of his report, space programs around the world adapted their equipment and procedures specifically to reduce debris creation. During an interview years later, one of Kessler’s co-workers referred to Kessler’s 1978 concept of cascading collisions as “the Kessler Syndrome” – the name has stuck ever since.³⁹

Given the increasing number of spacecraft and amount of debris, the already difficult job of avoiding other objects in space has become exponentially harder, forcing spacecraft operators to expend even more time, money, and energy on maneuver planning

³⁷ <http://spaceflight.nasa.gov/realdata/tracking/index.html> (accessed May 19, 2010).

³⁸ Changes to NASA’s budget for the International Space Station are on slide 9 in the budget briefing at: http://www.nasa.gov/pdf/420990main_FY_2011_Budget_Overview_1_Feb_2010.pdf (accessed May 19, 2010).

³⁹ Don Kessler describes the 1978 report and how the name “Kessler Syndrome” appeared at: <http://webpages.charter.net/dkessler/files/KesSym.html> (accessed May 19, 2010).

and collision avoidance. In the early years after Sputnik, the small number of objects in orbit allowed operators much latitude with regard to collision. In contrast, before the collision, Iridium operators had to consider over 1000 predicted conjunctions each week where another object passed within 5 km of an Iridium spacecraft. A report issued minutes before the collision showed 151 closer predicted approaches than Iridium-33 and Cosmos-2251, and it was not even the closest prediction for Iridium-33, let alone the entire Iridium constellation.⁴⁰ However, this was the only prediction that resulted in an actual collision. With over 1300 additional pieces to avoid post-collision, the number of predicted conjunctions has increased even more. If the critical conjunction was lost in hundreds of other predictions before, the situation has only become worse. The increased level of risk also drives insurance premiums higher for commercial spacecraft companies. All of these increases in time, money, and energy eventually reach consumers in the form of higher fees.

Collisions in space can affect the entire space community. The Soviet Union and the United States developed destructive anti-satellite weapons programs during the Cold War that produced debris. The Soviets tested their co-orbital program 20 times starting in 1968, yet only a few pieces of debris remain in orbit today. The U.S. tested its kinetic program only once in 1985, and all 285 pieces of the target P-78 Solwind spacecraft have re-entered the atmosphere.⁴¹ Both countries had terminated these programs by 1988.

⁴⁰ T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," 2.

⁴¹ NASA lists of debris events include current status on Soviet tests, starting with Cosmos 249, and the single US test vs P-78 Solwind. See NASA Orbital Debris Program Office, "History of On-Orbit Fragmentations, 14th Edition," (Houston: NASA Johnson Space Center, June 2008).

The long-term hazards to all spacecraft from debris far outweighed any short-term benefit from destroying an opponent's single spacecraft, especially considering the number of targets at higher altitudes where debris lasts for centuries. Despite this awareness, two decades later, China's leaders chose to launch a destructive weapon to collide with a Chinese weather satellite (the FY-1C of the Fengyun series) in a polar orbit near 860 km in 2007. This deliberate collision produced over 2000 pieces of high-velocity debris that will take hundreds of years to descend into Earth's atmosphere. With this decision, Chinese leaders produced "the worst contamination of low Earth orbit in history."⁴² With these pieces crossing through high-value polar orbits, China's leaders already have caused many spacecraft owners to shorten the lifespan of their vehicles with additional fuel-consuming collision avoidance maneuvers.

Both the deliberate Chinese collision and the accidental Iridium-Cosmos collision two years later provide plenty of fresh proof that collisions create hazards for all spacecraft. Only Chinese leaders have control over their ability to direct additional deliberate collisions, but the collective space community can commit resources to work together in order to prevent further accidental collisions. Considering this analysis of the Iridium-Cosmos collision specifically and debris hazards in general, collision avoidance failure results in significant consequences for the entire space community.

⁴² NASA Orbital Debris Program Office, "History of On-Orbit Fragmentations," 1, 5, and 386.

CHAPTER 2

Collision Avoidance Factors

“SOCRATES did predict a close approach between Iridium 33 and Cosmos 2251 at the time of the actual collision in each of the 14 reports in the week leading up to the event. None of these, however, made the Top Ten list.”

—Dr T.S. Kelso¹

Collision avoidance planning relies on four interrelated factors: external policy, internal policy, collision-avoidance software, and sensor data. External policy results from efforts of both international and national regulation – spacecraft owners and operators may have little influence over the content of external policy. Internal policy and collision-avoidance software choices result from specific decisions within each organization. The final factor, sensor data, results from observations of objects in space using various sensors, typically produced by third parties with varying levels of accuracy.

External Policy

The most obvious external policies are international treaties and national laws. The foundation for external policy is the 1967 “Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies,” more commonly known as the “Outer Space Treaty.” As of 1 January 2008, 98 countries are parties to the treaty, and another 27 have signed the treaty,

¹ One collision avoidance software tool is named Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES). Opening quote from T.S. Kelso, “Analysis of the Iridium 33-Cosmos 2251 Collision,” 2.

but have not yet completed ratification.² This treaty promotes peaceful cooperation between nations regarding their space-going activities. References in three of its articles obliquely suggest states should avoid the creation of debris, but it offers no specifics.³ Considering this treaty went into force while both the United States and the Soviet Union had active anti-satellite weapons programs designed to create lots of debris, one should expect rather vague wording. The treaty forms the original international framework for space activity, but many lawyers associated with space law are finding it obsolete and in need of replacement or modification, particularly regarding commercial mining.⁴

A lunar version of America's Gold Rush in the 1800s could be on the horizon. The Apollo missions discovered that the Moon surface contained vast amounts of valuable minerals, but without water, excavating those minerals was not practicable. Since scientists have long considered the surface of the moon completely arid, NASA shocked everyone with the recent confirmation of significant amounts of water at both the Moon's poles.⁵ Figure 12 shows a sample image from a NASA sensor attached to India's Chandrayaan-1 spacecraft. This discovery has opened up the real prospect of

² "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies," January 27, 1967, United Nations Office for Outer Space Affairs, <http://www.unoosa.org/oosa/SpaceLaw/outerspt.html> (accessed May 19, 2010).

³ National Research Council, *Orbital Debris*, 186.

⁴ Wayne White is a respected lawyer with extensive writings on space law, especially on areas involving private property rights in space. Wayne White, "The Legal Regime for Private Activities in Outer Space" (Presented at "Space: The Free Market Frontier" on March 15, 2001, http://www.spacefuture.com/archive/the_legal_regime_for_private_activities_in_outer_space.shtml) (accessed May 19, 2010).

⁵ NASA issued a news report on September 29, 2009 about confirming water on the Moon. Available at: <http://www.nasa.gov/topics/moonmars/features/moon20090924.html> (accessed May 19, 2010).

commercial mining on the Moon, since potential mining operations at the lunar poles may not need large, heavy containers of water transported from Earth. NASA's latest reports include data on water creation, migration, deposition, and retention in over 40 locations, proving the Moon is much more dynamic than previous missions had suggested.⁶ Since the current "Outer Space Treaty" dictates that no nation can own any celestial body, it is unclear who can regulate what happens on the Moon as lunar prospectors rush to capitalize on this new opportunity.

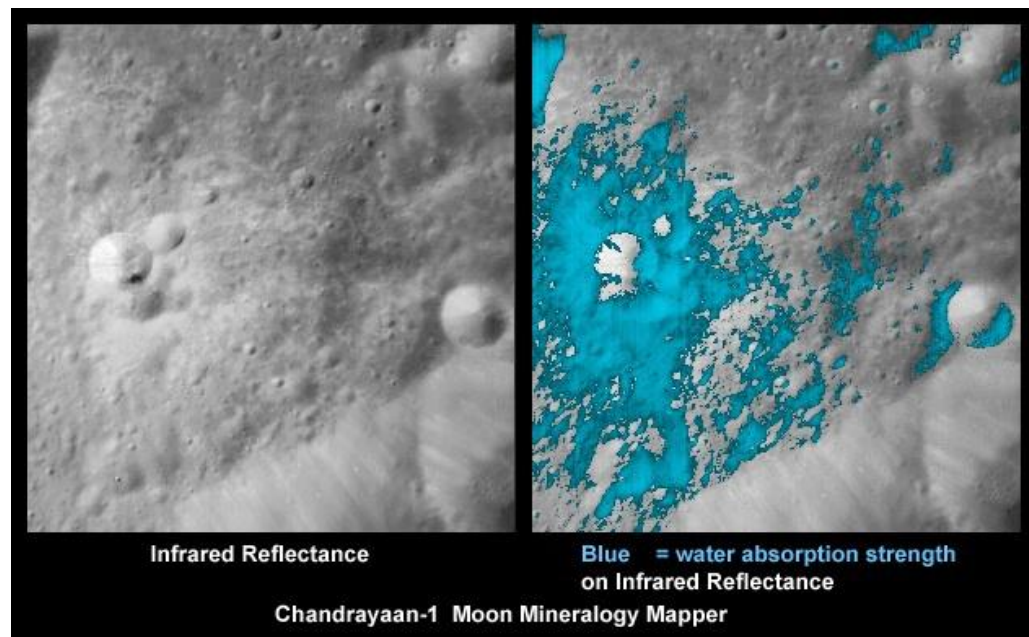


Figure 13. Confirmation of Water on the Moon⁷

⁶ Continued mission data confirmed a very dynamic water environment at both poles of the Moon. Details available at: http://www.nasa.gov/home/hqnews/2010/mar/HQ_10-055_moon_ice.html (accessed May 19, 2010).

⁷ NASA image. Available at: <http://www.nasa.gov/topics/moonmars/features/clark3.html> (accessed May 19, 2010).

Increased traffic to and from the Moon will produce paint flecks and rocket exhaust particles and create more opportunity for debris pieces that can wreak havoc on existing spacecraft as described in the previous chapter. To the entrepreneurs, investors, and future customers, the potential benefits from these new opportunities will outweigh debris concerns. As a result, the collective space community will have to deal with these additional risks with or without new international legal instruments.

The 1972 “Convention on International Liability for Damage Caused by Space Objects,” commonly known as the “Liability Convention,” was an early attempt at resolving one concern that the “Outer Space Treaty” did not adequately address. The “Liability Convention” broadly outlines issues regarding the assignment of fault in any space incident, placing responsibility for damages on the owner of the offending spacecraft. Written during a period when there were few space programs, this document relies on several key assumptions. For example, it assumes any space object capable of inflicting damage would have a recognizable owner, which is contrary to the reality that tiny, uncataloged, and otherwise anonymous pieces of debris are capable of inflicting serious damage to other spacecraft.⁸ Additionally, while the “Liability Convention” provides reasonable concepts regarding liability, it has no enforcement authority. Owners must agree to take responsibility for damages. The closest the Liability Convention’s resolution process has ever come to actual use was in 1978, when the Soviet spacecraft Cosmos 954 spread radioactive debris from its nuclear reactor over northern Canada during its uncontrolled reentry. The USSR chose to pay Canada less

⁸ National Research Council, *Orbital Debris*, 186.

than half of the amount requested to cover cleanup costs, but the Soviets never admitted liability.⁹ Although Canada cited passages from the “Liability Convention” in its request for compensation, the settlement did not follow the process outlined in the treaty; therefore, the USSR’s payment does not provide precedence for the applicability of the convention’s provisions.¹⁰ Clearly, the “Liability Convention” only partially solved the issue it attempted to address. As of 2010, existing international legal instruments still do not address all the concerns of the modern space community. As with many treaties that intentionally lack enforcement mechanisms, each signatory nation-state has the responsibility for enforcing these treaties within its own borders.

National policies regarding space activity vary widely, and, like treaties, these policies are external to the organizations that actually conduct space activities. Over 60 different nations operate over 1100 satellites currently, and each government makes its own sovereign choices about whether or how to regulate activities involving satellites launched and/or operated from within its territory.¹¹ For example, US policy is very stringent regarding launch certification. In contrast, India’s leaders do not require any certification that Indian launch vehicles are prepared properly and should function safely, even though India also provides routine space launch opportunities to many other

⁹ Canada spent almost C\$14 million total in cleanup costs and requested reimbursement of a little over C\$6 million. The USSR paid exactly C\$3 million. All amounts per April 2, 1981 release. “Settlement of Claim between Canada and the Union of Soviet Socialist Republics for Damage Caused by ‘Cosmos 954’” (Released on April 2, 1981, available at: http://www.jaxa.jp/library/space_law/chapter_3/3-2-2-1_e.html) (accessed May 19, 2010).

¹⁰ Wayne White, “The Legal Regime for Private Activities in Outer Space.”

¹¹ William Lynn, US Deputy Secretary of Defense, provided these statistics during a speech at the National Space Symposium, Colorado Springs, CO, on 14 Apr 10. Available at: <http://www.defense.gov/speeches/speech.aspx?speechid=1448> (accessed May 19, 2010).

nations.¹² Spacecraft operators do not have direct control over external policies regarding collision avoidance. Fortunately, treaties and laws tend to change infrequently once established, allowing operators to adapt to the occasional changes and move on. External policy alone cannot succeed in mandating collision avoidance, but these treaties and national laws shape the environment affecting the remaining factors of collision avoidance.

Internal Policy

Another important factor of collision avoidance is internal policy – the internal set of rules that govern how an organization chooses to conduct operations. The most powerful force driving internal policy is money.¹³ Any national or corporate organization that spends millions of dollars to develop, launch, and operate a spacecraft will take a dim view of anyone or anything that jeopardizes that investment. As a result, all spacecraft owners and operators consider collision avoidance on a daily basis.

Organizational leaders make decisions regarding numbers of satellites necessary for a mission, vehicle design, sources of spacecraft tracking data, and numerous other variables involved with operating a spacecraft. For example, Iridium had designed their constellation and software with the ability to adapt quickly to any loss of service from a single spacecraft. Iridium's communications service experienced only a minor

¹² K. K. Nair, *Space: The Frontiers of Modern Defence* (New Delhi, India: Knowledge World in association with Centre for Air Power Studies, 2006), 97.

¹³ Jim Oberg, *Space Power Theory*, 104.

degradation after the collision with Cosmos-2251 destroyed Iridium-33 – most customers never even noticed.¹⁴ Within two weeks, Iridium had restored the constellation, moving Iridium-91, an orbiting spare, into position to cover Iridium-33's place in the constellation.¹⁵ For most Iridium customers, the loss of an entire spacecraft did not influence their activities on the day of the collision or at any time thereafter. Iridium's leaders built its internal policy around providing continuous service to its paying customers, and it accomplished that goal, even after total loss of a spacecraft.

Spacecraft owners have many options on how they will do business. Their internal policies reflect their choices regarding how to balance cost and risk while still complying with the external policies from their local governing authority. Since changing internal policy can be as simple as writing a memo, it is the most flexible of the four factors discussed in this chapter.

Collision-Avoidance Software

Collision avoidance-related software choices reflect the internal policies of an organization, since the software provides the mechanism for implementing those policies. The space community uses orbit determination software to predict where vehicles are going and whether they will be in danger from other objects. Spacecraft owners must

¹⁴ Iridium PA statement, 9 Mar 09
<http://www.iridium.mediaroom.com/index.php?s=43&item=892&printable> (accessed May 19, 2010).

¹⁵ <http://www.rod.sladen.org.uk/iridium33collision.htm> (accessed May 19, 2010).

decide whether to purchase their own software (and employ enough people to analyze the results) or contract out this function to an external entity.

Owners have a variety of options. The most expensive option is to operate a network of spacecraft, sensors, and orbit determination software within the same organization. An example of an organization that has chosen this option is the French space agency, Centre National d'Etudes Spatiales (CNES). CNES operates its network in order to make its own decisions regarding risks to its assets without solely relying on another organization to provide the data and analysis necessary for collision avoidance.¹⁶ A less expensive option is to rely on an outside organization to provide collision avoidance analysis. For example, the Center for Space Standards & Innovation (CSSI), a private entity in Colorado Springs, gathers publicly available orbit predictions from the US military and inputs those predictions into its own software.¹⁷ CSSI then uses that software to predict whether a subscriber's vehicle will be in danger of colliding with any other object.¹⁸ CSSI began this process in 2004 as a public service. As of February

¹⁶ <http://www.space.com/news/090227-space-collision-questions.html> (accessed May 19, 2010).

¹⁷ In Jan 2010, US Strategic Command (USSTRATCOM) took responsibility for the US military's Commercial & Foreign Entities (CFE) program from Air Force Space Command as planned, renaming it SSA Sharing. USSTRATCOM's Joint Space Operations Center (JSpOC) provides orbit information to registered users using the website www.space-track.org. As of 1 Jan 2010, the JSpOC checks orbit predictions for all active spacecraft for conjunctions daily. Richard Boltz and Zachary Owen, "Steps Toward International Space Situational Awareness" *High Frontier* (Air Force Space Command) 6, no.2 (February 2010): 35 and 37.

¹⁸ Description of CSSI's software at: <http://celestrak.com/SOCRATES/> White paper analysis at: <https://www.agi.com/downloads/support/productSupport/literature/pdfs/whitePapers/socrates.pdf> (May 2005) (accessed May 19, 2010).

2010, CSSI supports 18 organizations operating over 260 active satellites.¹⁹ These organizations have chosen to trust CSSI to predict potential collisions accurately.

CSSI predicted Iridium-33 and Cosmos-2251 would miss each other by over 500 meters in its report less than 1 hour prior to collision, generating questions about the wisdom of trusting someone else with the safety of an organization's moneymaking assets.²⁰ Analysis of CSSI's software would show that it compared the available orbit predictions of all objects according to its design parameters, indicating the projected false miss distance did not result from faulty programming. Since CSSI's software performed as designed, the faulty report indicates a problem with the final factor of collision avoidance, the sensor data and associated orbit predictions for each object.

Sensor Data

No collision-avoidance software can make accurate conjunction assessments without valid orbit predictions based on accurate sensor data. It is not enough to know only where one vehicle is in space. To predict and validate a safe route, orbital analysts must also know where every other spacecraft and piece of debris will be relative to a satellite's predicted position for any given time. Finding these relative positions requires multiple steps. First, individual sensors must gather raw data by observing the flight paths of orbiting objects. Second, this raw data feeds into orbit determination software to

¹⁹ Current list in Kelso, "How International Collaboration is Improving Space Situational Awareness," *High Frontier* (Air Force Space Command) 6, no.2 (February 2010): 24.

²⁰ T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," 2.

generate an orbit prediction for each observed object. Finally, these orbit predictions feed into the collision-avoidance software to generate predictions of collisions and near misses between objects based on their current orbit predictions.

Although this process sounds relatively simple, maintaining accurate orbit predictions over time remains the most challenging aspect of orbit prediction. Orbits are affected both by intentional maneuvers (for safety or mission requirements) and by the dynamic forces that act on all objects in space. These forces dictate that no spacecraft can remain precisely in one orbit over time. Once rocket propulsion brings a spacecraft up to orbital speeds in the appropriate direction, gravity becomes the main force involved in sustaining orbit.

Gravity varies over time in any given location, affecting orbits significantly. Some variations result from the n -body effect when a source of gravity besides the Earth exerts small, but noticeable influences on an object's trajectory. Common sources include the Sun, Moon, Mars, and Jupiter. Because these sources are far away, their influences are not enough to wrest an object out of Earth orbit, but the influences are still significant enough to alter an object's trajectory.

Earth's dynamic oblateness also produces variations in Earth's gravity. The Gravity Recovery and Climate Experiment (GRACE) mission to map the Earth's gravity field began in 2002, showing significant gravity field variations across the planet. Ongoing observations from the two GRACE spacecraft show that the locations and intensities of these variations also change considerably from one month to the next. Figure 14 shows a snapshot of the variations in Earth's gravity charted during 2003. Note the unusually high gravity regions shown in red in the North Atlantic, the Middle

East, and near the Philippines. Blue areas in the Indian Ocean, China, and central Africa indicate regions where the GRACE spacecraft recorded lower gravity at the time. Long-term GRACE data also reflects significant variations over time for any given location. For example, the monthly data for South America shows variability across the spectrum from lowest gravity to highest gravity in less than 1 year.²¹

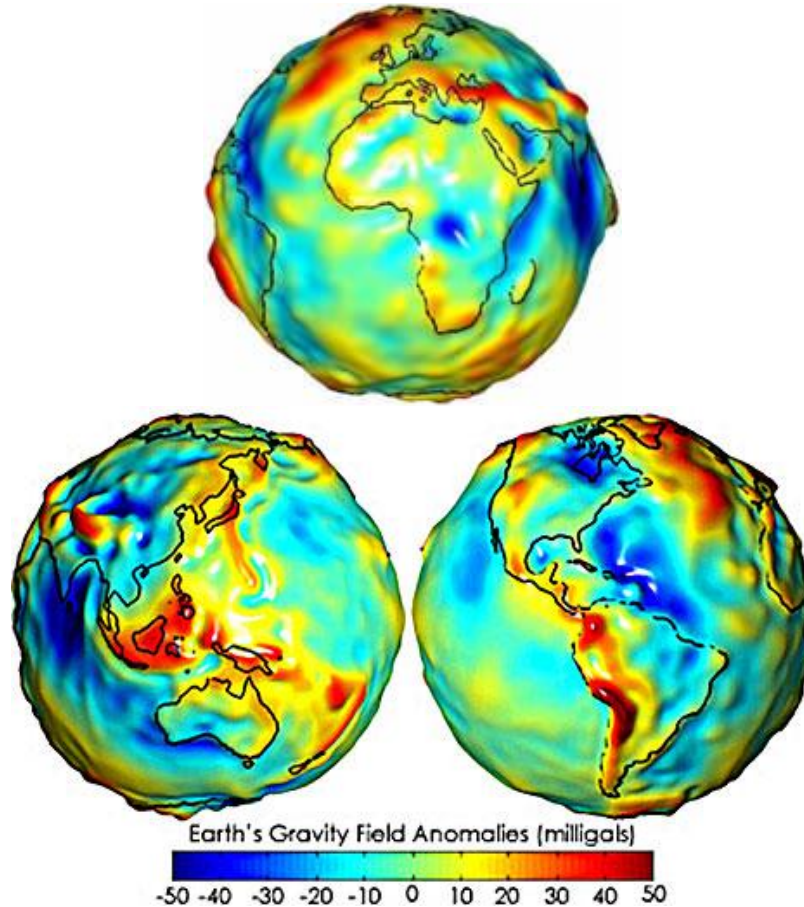


Figure 14. Earth's gravity field variations in 2003²²

²¹ Month-to-month data: ftp://podaac.jpl.nasa.gov/pub/tellus/monthly_mass_grids/chambers-destripe/dpc200711/browse/anim/csr300lnd_RL04_500x260.gif (accessed May 19, 2010).

²² Snapshot at: <http://gracetellus.jpl.nasa.gov/information/> (accessed May 19, 2010).

Operators know these unpredictable variations in gravitational forces combine to push, pull, and twist orbits just enough to negate previous predictions constantly. While active spacecraft can maneuver to re-establish a desired orbit, debris and other objects cannot. The only way to confirm the effects of perturbations is to generate continuously fresh observations.

Most observations come from multiple types of ground-based sensors. No single type of ground-based sensor is sufficient by itself to determine the current position of an object in orbit. While sensor types can include infrared and radio telescopes, electro-optical telescopes and radar sensors form the backbone of spacecraft observations. Electro-optical telescopes are the best tool for determining angular measurements to an object, such as azimuth (the direction to the object, expressed in degrees from north), and elevation (the angle from the horizon, expressed in degrees from horizontal), but telescopes do not accurately measure range (the distance to the object, expressed in kilometers or miles). In contrast, radars provide excellent range information based on their ability to measure returned radar energy precisely, but radars have a higher margin of error regarding azimuth and elevation angles when compared to electro-optical telescopes.

Space-based options exist for information about objects. Newer spacecraft designs incorporate Global Positioning System (GPS) receivers, providing their operators with accurate enough position information to provide another source for observations regarding those spacecraft. Space-based sensors can provide observations on other objects from above clouds without the field-of-view limitations on ground-based sensors. In 1996, the Ballistic Missile Defense Organization launched the Mid-course Space

Experiment (MSX) technology demonstration to test methods of tracking missile warheads passing through space, but its Space-Based Visible (SBV) 15-cm telescope also produced useful tracks on spacecraft at geo-synchronous orbits.²³ As a result, MSX/SBV served as a contributing sensor for the US Space Surveillance Network until its demise in 2008. The resulting follow-on operational program plans to launch its first Space-Based Space Surveillance (SBSS) spacecraft later this year as a pathfinder built specifically for tracking space objects as opposed to the unexpected MSX/SBV capability. However, both MSX/SBV and the SBSS pathfinder focus on the easier challenge of geo-synchronous orbits, where spacecraft move at much slower speeds 36,000 km from Earth. Future objective SBSS concepts add the ability to track objects in low Earth orbits and would be more useful in dealing with traffic in polar orbits.²⁴

In light of the dynamic environment described earlier, orbital analysts must have a constant stream of position information for each object in order to update orbit predictions and associated comparisons for collision avoidance. Orbital analysts combine observations of a single object from multiple types of sensors in order to form the most accurate orbit prediction possible for that object. The growing numbers of vehicles and objects in any given volume of space require greater effort to prevent the uncertainty that drives leaders to direct unnecessary maneuvers or to accept higher risk.

On a final topic, the extremely high speeds of low Earth orbit (over 7 km/s) preclude any real opportunity to assess and avoid a collision in near-real time. An

²³ Approximately 6 inches

²⁴ MSX/SBV and SBSS information available at: <http://www.boeing.com/defense-space/space/satellite/sbss.html> (accessed May 19, 2010).

emergency maneuver “in the blind” theoretically may be possible an hour prior to a predicted collision, but there is no split-second opportunity to observe an object and “swerve” from a collision. Access to an available antenna to send commands and/or time involved in pointing a thruster in the correct direction means the last realistic opportunity to command thruster firing occurs while the other object is still “over the horizon.” In order to execute a typical collision avoidance maneuver, planners take three to four days of advance warning in order to validate that the new orbit will be safe and to minimize fuel usage.²⁵ Since space refueling operations are not much past a single proof-of-concept experiment, the main life-limiting resource for a spacecraft is fuel. Considering the dynamic environment discussed earlier, conjunction assessments generated more than four days in advance are not useful for maneuver planning, and planners must consider the possible variations in both orbits in those remaining four days.²⁶

Many members of the space community have suggested that all sensor operators should contribute to a large interconnected network.²⁷ Currently, some sensor operators do belong to smaller networks, but many do not. Those networks do not connect to each other, limiting the best possible accuracy for awareness for collision avoidance, and this

²⁵ Joel Achenbach, “Astronauts Evacuate Space Station Temporarily During Collision Scare,” Washington Post, March 19, 2009, <http://www.washingtonpost.com/wp-dyn/content/article/2009/03/12/AR2009031201900.html> (accessed May 19, 2010).

²⁶ Derived from variations in Iridium-Cosmos reports prior to collision. T.S. Kelso, “Analysis of the Iridium 33-Cosmos 2251 Collision,” 2.

²⁷ For example, Russian scientist Vladimir Agapov suggested this concept at a UN Institute for Disarmament Research conference in June 2009. Page 10 of report at <http://www.unidir.org/pdf/ouvrages/pdf-1-92-9045-009-E-en.pdf> (accessed May 19, 2010).

independence costs sensor operators, orbital analysts, and planners around the world many additional hours working separately.

The accuracy of each orbit prediction directly correlates with the recency, quality, and types of sensor observations available for that object. Therefore, decisions affecting sensor data collection and dissemination are vital for space situational awareness. With more awareness, space operators can optimize their collision avoidance techniques, expanding mission opportunities instead of wasting time and fuel with unnecessary maneuvers or losing more spacecraft in collisions.

In summary, operators deal with collision avoidance considerations every day, applying four factors. External policy comes from laws and requirements from outside the organization. Internal policy from organization leaders govern how the organization will accomplish its mission within the external policy framework. Collision avoidance software selection reflects internal policies regarding orbital safety. Sensor data provides the inputs for that software, and more high-quality data produces more accurate warnings from collision avoidance software, enabling better decisions. Since sensor data provides the basic foundation of collision avoidance, sensor data represents the most direct improvement opportunity of the four. Efforts to improve external policy alone through “rules of the road” from the United Nations can only address the outer shell; sensor data improvement works at the heart of the matter. With this understanding of important collision avoidance factors, the next two chapters examine the technical and psychological obstacles currently impeding further improvement.

CHAPTER 3

Technical Challenges

“Space-faring nations need to develop common protocols and languages, so that we can share via networks the sensor information and pass it more efficiently and effectively.”
—General Kevin P. Chilton, CDR USSTRATCOM¹

The discussion in the previous chapter illustrates that the task of avoiding collision in space is complex and challenging. While every spacecraft operator desires to avoid colliding with other objects in space, current technical difficulties may obscure the path to success on a given day. Technical solutions are possible, but they require a commitment of time, money, and political will. This chapter explores a sampling of the difficulties and describes possible solutions awaiting decisions. The next chapter will discuss key psychological factors also wrapped into these decisions.

The authors of the “Analysis of the Technical Feasibility of Building an International Civil Space Situational Awareness System” describe four technical hurdles, specifically with different orbit prediction techniques and models, varied data formats, increased sensor tasking complexity, and required data security. In all cases, the authors describe possible solutions. Their analysis represents useful initial material for informing decision-makers considering what to do in order to move forward. The authors recognize the fact that political challenges and trust issues influence technical decisions, but focus

¹ Kevin Chilton, Speech to the 5th Ilan Ramon Annual International Space Conference, Israel, January 27, 2010, http://www.stratcom.mil/speeches/28/5th_Ilan_Ramon_Annual_International_Space_Conference (accessed May 19, 2010).

their analysis on the technical responses.² In contrast, this thesis specifically addresses the psychological factors influencing those political challenges in the next chapter. This chapter focuses on the technical aspects decision-makers should consider in order to move beyond passive catalog maintenance toward active and effective collision avoidance.

As discussed in the previous chapter, several factors complicate orbit prediction. For example, various software packages cater to different niche users, employing different atmosphere and gravity models.. The fundamental trade when selecting software becomes speed vs precision, and each software developer optimizes differently. Analytic techniques emphasize speed, while numeric techniques provide greater accuracy.³ Each option has value, so a robust system applies a combination of techniques in order to provide planners and operators with the best possible information for collision avoidance. Users must understand that an instant answer has inherently less accuracy, while a precise answer will take some time. Conversion between techniques dilutes precision, and misunderstood reference databases can produce useless predictions. Fortunately, the technical specifications of each option are available for leaders to compare. Decision-makers must consider how fast they require a “good enough” prediction, and involving many decision-makers in an international solution may produce lively discussions. A single software solution is not necessary, but decision-makers

² Brian Weeden and T.S. Kelso, “Analysis of the Technical Feasibility of Building an International Space Situational Awareness System” (www.secureworldfoundation.org/siteadmin/images/files/file_378.pdf), 9 (accessed May 19, 2010).

³ Ibid., 4.

should set expectations to match the capabilities they select regarding speed and accuracy.

Another technical challenge involves lack of compatibility of all the various sensors capable of tracking objects in space, impeding machine-to-machine interface among incompatible sensors. During construction of each sensor, the owner optimizes the sensor's design for a specific purpose. Owners' purposes vary widely and are not necessarily compatible with each other. Unless a sensor designer deliberately incorporated the ability to collaborate with others, the sensor in question may have limited ability to share its raw data with anyone else. However, since the space community firmly grasps orbital mechanics, each sensor observation contains useful information, albeit perhaps in a different format or presentation method.⁴ Without standardized formats for reporting observations machine-to-machine, however, the required human interpretation delays data utility and adds expense.

Some technical obstacles stem from current internal policies. For example, the US military's Joint Space Operations Center (JSpOC) policy currently does not allow its personnel to use spacecraft-reported position information to update its catalog, but allows its personnel to use such information to perform collision avoidance only. Leaders wrote the existing catalog maintenance policy during the period before spacecraft had GPS receivers on board, when ground-based sensors provided the only reliable position information. The previous Director of the JSpOC, Colonel Richard Boltz, co-authored a recent article with Major Zachary Owen, the JSpOC's Chief of Operations Assessment,

⁴ Weeden and Kelso, "Analysis of the Technical Feasibility of Building an International Space Situational Awareness System," 5.

indicating the need for leaders to review and modify this policy.⁵ From the previous chapter, decision-makers can change internal policies relatively easily, after careful review, of course.

With appropriate policies in place, future sensors could apply a declared standard for machine-to-machine data reporting, but many existing sensors would require a given network to develop or modify software in order to incorporate those observations. Current networks already have compatible software for the sensors within their network, but just as different sensors have different report formats, not all networks share the same format either. In other words, the key data necessary to make smarter collision avoidance decisions is spread out across incompatible sensors and networks of sensors. However, for the right price and schedule, software developers can produce the necessary algorithms to bridge these compatibility difficulties. The remaining associated challenge is paying for this software for each incompatible sensor whose owner wants to contribute observations, but cannot absorb the cost of the software internally. Each existing network has solved this format challenge to serve that network's purposes using various sensors, so technical solutions tailored to incorporate unique sensors are possible.⁶

Another technical challenge arises from the sheer volume of collision avoidance messages for owners of multiple spacecraft. In the years prior to the Iridium-Cosmos collision, the JSpOC routinely sent collision warnings to Iridium. At a meeting in 2007,

⁵ Richard Boltz and Zachary Owen, "Steps Toward International Space Situational Awareness" *High Frontier* (Air Force Space Command) 6, no.2 (February 2010): 35.

⁶ Weeden and Kelso, "Analysis of the Technical Feasibility of Building an International Space Situational Awareness System," 5.

Iridium's Vice President for Government Relations, retired US Air Force Lieutenant General John Campbell stated that Iridium's planners could not use these warnings, partly because they routinely received 400 such warnings per week. Moreover, each warning had enough uncertainty that Iridium's leaders decided that the probability of collision was less than the probability of wasting fuel on unnecessary collision avoidance maneuvers. This choice to accept the possibility of a catastrophic collision may have made sense in the early years of space activity, but the growing number of spacecraft in polar orbit, 75 of which belonged to Iridium, effectively made this a matter of not if, but when, a collision would occur. In that 2007 meeting, Campbell commented that, even though "clearly that risk was something bigger than zero," Iridium's leaders ultimately decided to "grit our teeth and hold our breath."⁷ Unfortunately, Iridium's internal policy for dealing with the flood of collision avoidance messages ultimately led to the catastrophic collision in 2009.

The solution to this problem, interestingly, is access to a greater number of sensor readings from more locations, especially for spacecraft without GPS receivers that cannot report their own position accurately. As discussed in the previous chapter, many different forces act on objects in Earth orbit, and painting an accurate picture of the relative position of objects in space presents challenges. With the uncertainty associated with normal deviations at orbital velocities, numerical representations of object locations do not resemble a point on a standard two-dimensional (XY) graph. Instead, orbit determination software produces a "covariance ellipsoid" which resembles a bubble on a

⁷ John Campbell, et al., "Forum on National Security Space: Examining Codes and Rules for Space," 8 - 9.

three-dimensional (XYZ) graph. The object is located somewhere within that bubble. Collision avoidance starts with identifying when two bubbles will meet to produce possibilities for collision.⁸

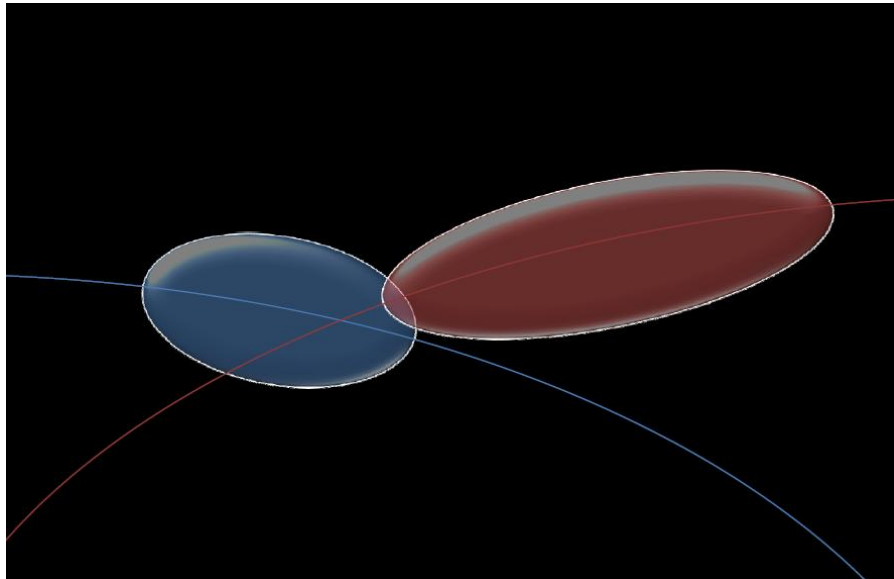


Figure 15. Covariance Ellipsoids Showing Possible Collision

Low numbers of sensor observations, sensor observations of only one type, or a lack of recent observations will produce larger bubbles, generating many collision possibilities simply due to the larger ellipsoid sizes. Conversely, many varied types of recent sensor readings will result in a smaller covariance ellipsoid, reducing the number of false alarms. Continuous GPS-based reporting from spacecraft into a network could relieve the pressure on sensors for continuous observation of those spacecraft, since the external reference to the GPS constellation reduces the associated uncertainty significantly. Sensors could reduce observations of those reporting spacecraft to periodic calibrations only, focusing more attention on debris and other non-reporting objects.

⁸ F. Kenneth Chan, *Spacecraft Collision Probability* (El Segundo, CA: The Aerospace Press), 13.

Finally, one unavoidable challenge in the fight against space collisions is the necessity for reliance on external sources for time-sensitive data. Due to the distances and speeds involved in spaceflight, there is no way for on-board sensors to deal with crossing pattern collision avoidance. Circling the globe in 90 minutes at over 7 km/sec, the curvature of the Earth alone blocks visibility of objects approaching a given orbit at similar speeds. Only off-board processes can provide operators with the awareness required to avoid “t-bone” collisions like Iridium-Cosmos.

Planners require timely access to accurate information from external sources to ensure their spacecraft will avoid known objects. The technical challenges have possible solutions. Existing networks have established data formats, accuracy thresholds, and reliability information. With some time and money, decision-makers can adapt the necessary equipment and policies from these existing solutions to enable machine-to-machine transfer across multiple networks. This effort would reduce the technical obstacles currently impeding collision avoidance, but the psychological factors covered in the next chapter will prove more difficult.

CHAPTER 4

Psychological Challenges

“It must be remembered that, among all changes, the nature of man remains much the same; the personal equation, though uncertain in quantity and quality in the particular instance, is sure always to be found.”

—Alfred Thayer Mahan¹

Human factors are far more challenging to overcome than technical ones. It would seem to be a given that those who are able to make orbit would understand that improving collision avoidance is good, since debris creation reduces the number of available safe orbits. Unfortunately, many psychological obstacles exist that have prevented the space community from improving the current methods for collision avoidance. True progress requires decision-makers to acknowledge and address the competing fears of losing competitive advantage to some other decision-maker and the fear of losing a spacecraft in a collision. Current decisions across the space community reflect varying levels of individual ability to resolve this cognitive dissonance.

Every spacecraft operator has a unique reason for having a vehicle in orbit. These reasons may or may not be compatible with each other. As a result, one spacecraft operator may not want to share data with others, since a competitor could determine a way to use that information against them. Any endeavor involving more than one human has always involved basic factors such as fear, ownership, trust, power, safety, and security – activities in space are no different.

¹ Alfred Thayer Mahan, *The Influence of Sea Power Upon History, 1660-1783* (New York: Dover Publications, Inc., 1987), 89.

Fears of aggression in space are well founded. Not long after Sputnik's launch in 1957, both the United States and the Soviet Union began work on anti-satellite (ASAT) weapons programs in the 1960s. The first US operational ASAT programs were direct ascent weapons using nuclear warheads. In the 1970s, the United States developed an air-launched weapon that collided directly with its target. Using a very different concept, the Soviet Union developed a co-orbital program launched from the ground that maneuvered into position during two passes around the Earth, then exploded into fragments to destroy the target spacecraft.² Both countries' programs produced significant amounts of debris, but they also provided a demonstration of strength and technical prowess for their respective nations. Therefore, these ASAT programs provided both the U.S. and the Soviet Union with perceived advantages over each other that attracted other countries to embrace one or the other superpower.

During the Cold War, military leaders of both nations considered debris creation in space in the same context as thermonuclear war – both produced extreme long-term results, and both were real possibilities, given the military hardware available and on alert. Nuclear explosions on the ground and debris-producing events in space both create contaminated regions that all parties must avoid.³ Naturally, early commercial spacecraft operators viewed these ASAT tests and weapons with much concern, since the resultant

² Major Steven Petersen documented early Soviet and US ASAT programs and doctrine while serving as the Air Force Space Command-sponsored Research Fellow at the Airpower Research Institute. Steven Petersen, *Space Control and the Role of Antisatellite Weapons* (Maxwell Air Force Base, AL: Air University Press, May 1991), 5-7.

³ Major Scott Weston analyzed possible confrontations among space competitors, noting similarities between intentional debris creation in space and nuclear explosions on Earth. Scott A. Weston, "Examining Space Warfare: Scenarios, Risks, and US Policy Implications," *Air and Space Power Journal*, Vol XXIII, No.1, Maxwell Air Force Base, AL, (Spring 2009), 80.

debris posed a direct hazard to their commercial operations for years to come. From a military perspective, as space capability increased exponentially, decision-makers spread their reliance across satellite constellations arrayed at various altitudes, building in tremendous redundancy to ensure no nation could destroy all critical spacecraft at once. However, debris remained a concern, and by the late 1980s, both nations recognized that the dangers to all spacecraft from further debris-creating tests were counterproductive, and both halted their anti-satellite programs.⁴ Sadly, despite the obvious dangers, China's leaders re-ignited these fears in 2007 with the launch of their new debris-creating capability. With their technical choices for the test, Chinese leaders also deliberately chose to produce long-term debris hazards despite the previously mentioned Soviet and US examples of tests designed to limit debris production. These early and current debris-creating programs have fueled fact-based concerns that remain a huge hindrance to the cooperation necessary for better collision avoidance.

Ownership is another related powerful psychological factor. In this case, while no country or person owns outer space, each one owns its own spacecraft and technical prowess. A spacecraft operator, in his zeal to preserve his ownership of superior technology or equipment, may be reluctant to share his real capabilities with others, especially if those other entities are commercial or military competitors. This reluctance connects with trust.

Trust represents a significant psychological factor that contains an element of time. If two distinct parties intend to agree to follow a certain protocol, each must trust

⁴ Kerry Dumbaugh, "China-U.S. Relations: Current Issues and Implications for US Policy" (Washington DC: Congressional Research Service, October 8, 2009), 8.

that the other is going to abide by that protocol. This trust often requires periodic verification among participants in order to reassure each entity that trust remains in their best interest. For space situational awareness, both diplomatic and technical behavior will require this verification for continued trust.

The space community has no overarching compulsory judicial system or coercive penal system to govern the use of outer space, making diplomacy a vital part of space activity. The United Nations' Committee On Peaceful Uses of Outer Space (UN COPUOS) provides a forum for all parties to express various concerns. The UN COPUOS has been moderately successful in getting "buy-in" from some nations and coalitions for improved collision avoidance policy. For example in July 2009, the European Union provided a draft "code of conduct" to the UN committee. Ukraine has also provided a series of transparency and confidence-building measures intended to improve relations among former nation-state rivals.⁵ By design, however, international laws and treaties, no matter how sternly worded, rely on each party nation to enforce them internally, acknowledging and preserving the sovereignty of each nation.

As with other matters of international law, not every nation has the same approach to all aspects of space policy. From a previously mentioned example, India's leaders have chosen not to conduct or require safety certifications prior to launches, a requirement that US leaders consider essential.⁶ However, the rapidly compounding risk

⁵ UN A/64/138, 15 Jul 09, pp. 6-8 <http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N09/405/14/PDF/N0940514.pdf?OpenElement> (accessed May 19, 2010).

⁶ K. K. Nair, *Space: The Frontiers of Modern Defence* (New Delhi, India: Knowledge World in association with Centre for Air Power Studies, 2006), 97.

of space collision provides strong motivation for each space-faring country to establish national policies in support of any treaty aimed at avoiding such catastrophic mishaps and to trust that all other space-faring countries will do the same.

Diplomacy should also provide the environment for technical verification. Cold War treaty verification included scientific exchanges to examine technical capabilities under careful supervision for limited purposes. These periodic inspections worked for an environment where missiles remained in silos and bombers remained on alert. For the dynamic space environment where spacecraft pass each other constantly, technical verification of trust will require continuous opportunity to observe behavior of potential competitors. All verification should focus on position and movement in order to prevent this effort from becoming a front for determining spacecraft purpose and capability as a means to alter advantages among competitors.

Observer access limits should reflect their actual sphere of influence in order to preserve the trust that “observation” of technical capabilities will not devolve to political posturing, especially in regards to collision avoidance. If participant access to technical information is connected reasonably to safety of their own spacecraft and limited to collision avoidance planning, then the owners of that technical information may be reassured that the access cannot result in harm to their own capability. Sadly, the space community includes activists who seek to exploit technical access opportunities in order to hinder the actions of those who provided that technical information. Since many such activists have no actual responsibility for spacecraft and simply wish to advance ideologies, the space community could enhance trust-building simply with restricting access to technical information to planners directly involved with specific collision

avoidance activity. Planners should avoid activist attempts to coopt their technical access for a political victory, since the losing participants will be justified in labeling such planners as activist sympathizers and refuse them further trusted access. From the Cold War experience, US and Soviet technical inspections did not include outside parties seeking nuclear secrets or political bargaining chips that did not benefit the superpowers. Access to space technical information should include similar restrictions in order to build trust.

The pursuit of power is another obstacle to gaining the level of cooperation necessary for effective collision avoidance measures. A glaring example of this pursuit occurred in 2007. After many years without an active program in the world for destructive anti-satellite weapons, the Chinese test earned condemnation from around the world. Despite this condemnation, noted experts suggest that this test is part of a coordinated Chinese effort to achieve “great power status.”⁷ This effort would leverage their new technical prowess in space much like the United States and the Soviet Union did earlier with their Cold War ASAT programs. However, as noted earlier, only a few pieces of debris from the Cold War ASAT tests remain in orbit today, due to intentional US and Soviet technical choices. Instead, the Chinese chose to create a debris cloud that will continue to endanger spacecraft for centuries.⁸ With this test, Chinese leaders have ensured that everyone will note Chinese ASAT capabilities in any future discussion of space policy.

⁷ Dumbaugh, “China-U.S. Relations,” 8 & 24*n*.

⁸ NASA Orbital Debris Program Office, “History of On-Orbit Fragmentations.”

Contrast the Chinese brazen demonstration of power with the more responsible use of a similar capability by the United States. In 2008, the U.S. executed Operation Burnt Frost, modifying an anti-missile weapon to engage a derelict US spacecraft just prior to reentering the atmosphere with a fuel tank full of toxic hydrazine. Technical analysis indicated reasonable probability the tank would survive reentry and burst on impact with the ground to disperse the toxic fuel. Since the spacecraft had ceased to respond long ago, US operators had no ability to guide its reentry to a location away from populated areas. US leaders were concerned about the possibility of an event like the one previously discussed involving Russian leaders after the uncontrolled reentry of Cosmos 954 spread radioactive debris over northern Canada. Recognizing US liability for any damage or death resulting from this event, US leaders tasked the military to eliminate the possibility that the fuel tank could survive reentry.

Waiting until the spacecraft was near the atmosphere and about to reenter, US military planners designed an engagement with the modified anti-missile weapon that brought most resultant debris (and fuel) down to burn up in the atmosphere harmlessly within 48 hours from impact. This event demonstrated the use of a military capability for public safety, while underscoring that the US military clearly understood the need to avoid producing long-lasting debris. Although fear clouded the media coverage, the worldwide technical community understood and appreciated the US effort to protect

other nations from the possibility of an intact tank of toxic fuel landing in their territory.⁹ The negative media coverage illustrates how psychological factors can overwhelm technical facts. Rather than accept the possibility of responsible US use of power, the media remained scarred from the Chinese irresponsible use of power a year earlier, and reporters and producers chose to feed anti-US sentiments. Even the casual reader will note the obvious differences of 860 km (lasting centuries) compared to just above the atmosphere (lasting days) and weapons testing compared to preventing a derelict spacecraft from harming others. Sadly, some individuals will choose to reinforce preconceived notions and negative images despite such facts. Technical experts should guard against falling into similar selective observations, especially temptations to use positive collision avoidance efforts to advance other negative agendas.

Safety and security concerns are the final psychological obstacles to improving collision avoidance. Political and military leaders often refer to space as another “global commons” like the oceans.¹⁰ The open seas traditionally opened pathways for trade around the world, but as one nation found an advantage over another, the disadvantaged

⁹ Jim Oberg is a respected space expert with extensive NASA experience. He worked with Russian technical experts on the Shuttle-Mir program and the International Space Station, and he is often called to testify before the US Congress on the Russian space program. He analyzed the 2008 US shootdown of USA-193 and noted US openness regarding technical details about the need to act. Despite this openness and appreciation from technical experts in other nations, he noted much anti-US media coverage anyway. Jim Oberg, “US Satellite Shootdown: The Inside Story” *Spectrum Magazine*, Institute of Electrical and Electronics Engineers, August 2008. Available at: <http://spectrum.ieee.org/aerospace/satellites/us-satellite-shootdown-the-inside-story> (accessed May 19, 2010).

¹⁰ In 2009, Colonel John Shaw, Director of the USSTRATCOM Commander’s Action Group, wrote a comparison of maritime and space national-level strategy issues, identifying many similarities and differences that warrant additional consideration. John E. Shaw, “Guarding the High Ocean: Towards a New National Security Space Strategy through an Analysis of US Maritime Strategy” *Air and Space Power Journal*, Vol XXIII, No.1, Maxwell Air Force Base, AL, (Spring 2009), 55-65.

sought ways to shift the scales back into their favor – piracy produced a desire for naval security capability, leading to naval engagements with both pirates and other navies.

Merchant ships passing one another on the open seas still engaged in a form of conflict by seeking out swifter passages, more lucrative ports, and simply beating other ships to the goods. When ship-to-ship conflict ensued, the losers condemned the incident as piracy, while the winners celebrated their good fortune and towed their prize to port for ransom or sale. When one nation had lost more goods than it was willing to sacrifice, it chose either to arm its merchant ships, reducing their carrying capacity, or to provide armed escort from its navy, reducing the navy's ability to protect interests elsewhere. This action-reaction sequence continued until either one side permanently subdued its competition, both sides either tired of the conflict and quit, or both reached a point of uneasy equilibrium where neither could threaten the other.

Today, pure idealists stand on their principles to insist that space must be peaceful and that everyone should condemn anyone with any possibly aggressive capability. This idealistic view ignores history, insisting that humans have somehow become perfect when it comes to space. The current difference between space and sea commerce is that current “goods” in space are electronic and can be duplicated or altered without actually seizing control of the “ship.” Commercial spacecraft move millions of packets of information around the world every day, both as relays from other ground nodes and as products of onboard sensors. Like Navy logistics ships that resupply operations across the globe, military spacecraft do the same, moving millions of packets of information to and from military nodes. Copying information in transit is hard to detect. Moreover, this form of piracy does not produce debris. However, discovery of water on the Moon

makes Chinese plans to mine lunar Helium-3 a realistic possibility, and a Chinese “Treasure Fleet” moving to and from the Moon brings the discussion back to the sea analogies.¹¹

Just as with ships, a collision in space can upset the beehive of activity. In contrast with the sea, the resulting pieces of space “flotsam” become hazards to navigation for years, moving at high rates of speed crisscrossing the “sea lanes.” In light of the Chinese ASAT test in 2007, one can only wonder what those Chinese leaders were thinking. Just as the oceans became a source of conflict many centuries ago, space became an area for conflict during the Cold War. While the Soviet Union and the U.S. moved to information-based space conflict by the end of the Cold War, the Chinese have chosen a counterproductive destructive means that has complicated space operations for all, including themselves.

In closing, it is important to note that conspiracy theorists always emerge in an atmosphere of fear. Some such theorists attempted to paint the 2009 Iridium-Cosmos collision as some form of anti-satellite activity instead of a simple collision as discussed in previous chapters. Fortunately, within 2 weeks of the collision, orbital analyst Brian Weeden publicly documented Iridium's collision avoidance decision-making process and

¹¹ K. K. Nair, *Space: The Frontiers of Modern Defence* (New Delhi, India: Knowledge World in association with Centre for Air Power Studies, 2006), 131-132.

associated factors that resulted in “sins of omission and commission,” removing conspiracy theories from serious speculation.¹²

Starting Toward Solutions

Humans thrive in competition, improving their collective lot as one seeks to outdo another. When one gets an advantage, others seek to copy that advantage or seek out newer advantages that are either better than the first or capable of negating the first one. Many basic personality types desire any asymmetrical advantages when compared to others, becoming dissatisfied when anyone else has the advantage. For spacecraft operations, this situation produced the space race that resulted in the Apollo program placing humans on the Moon and many other groundbreaking activities in space. This drive remains visible today as corporations seek to outdo each other in terms of quality and quantity of products available from and through space. These corporations orbit their spacecraft alongside many military spacecraft seeking to confer similar military advantages to their respective nations. Many entities without spacecraft choose to join with a nation or corporation that does have spacecraft, offering money or other resources to offset their lack of space capability. Others seek out ways to deny space-based advantages to those that have them, developing and using jammers or kinetic attacks on

¹² Brian Weeden is considered a technical expert on space situational awareness issues. His analysis of the Iridium-Cosmos collision was swift, yet thorough. He is a former US Air Force orbital analyst currently serving as Technical Advisor for the Secure World Foundation. Brian Weeden, “Billiards in Space,” *The Space Review*. February 23, 2009. <http://www.thespacereview.com/article/1314/1> (accessed September 10, 2009).

ground nodes to reduce space capability directly. Indirect attacks target the cyber connection to and from space capabilities, and those employing this indirect approach develop and use means such as cutting fiber-optic connections, introducing computer viruses, and executing denial of service attacks.

Besides these economic, military, and information aspects, the diplomatic realm also provides opportunity to balance a perceived asymmetry. Weaker nations have traditionally used alliances to offset the power of others, leading some weaker competitors to seek advantage over the stronger competitors through their own nation's political system as well as the United Nations and other international bodies. Legal restrictions, however, only bind anyone to the extent that they allow themselves to be restricted. This concept is true whether it refers to the posted speed limit on the highway or activities on orbit – some personalities will respect every rule; others will not. One can spend much time and energy attempting to enforce every rule and seeking justice for every infraction, but that path leads to much frustration. Using the highway example, attempts to stop every speeder will require posting law enforcement officers every mile in sufficient numbers to stop every offending vehicle. If a driver chooses to obey speed limits only when a police officer is in sight, that person will speed often. However, in spite of many such people driving today, we do not see accidents at every intersection every day, despite over 250 million vehicles registered in the United States alone.¹³ All

¹³ The U.S. had 254,403,082 registered highway-capable vehicles in 2007. US Bureau of Transportation Statistics, “Number of US Aircraft, Vehicles, Vessels, and Other Conveyances” (Table covering 1960-2007, available at: http://www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html) (accessed May 19, 2010).

drivers, military and civilian, have a stake in maintaining the ability to continue on their way. If only for self-preservation, drivers will adjust their driving style to a particular environment in order to allow them to reach their destination. Attempts to enforce speed limits everywhere only results from missing the point of establishing a speed limit in the first place. Speed limits do not exist as a means of establishing governmental dominance over drivers; governments set speed limits to establish safe driving conditions. The actual conditions result from the level of self-imposed restraint among drivers at any given time. Speed limits encourage a restraint level that allows all drivers to arrive at their destination safely. This self-imposed restraint is comparable with internal policy related to collision avoidance as discussed in previous chapters.

Psychological obstacles regarding space operations are daunting, but surmountable with concerted collective effort. Strict attempts to enforce external policies such as more treaties, laws, regulations, and rules of the road will simply result in frustration. As with speed limits, each spacecraft owner/operator will interpret those external policies for their own benefit. More than one owner/operator ensures there will be more than one interpretation of any established set of rules. The self-imposed restraint on the highway results from each driver observing the surrounding cars and driving in a way that precludes collision. In contrast with automobiles, space operations require remote operations with off-board traffic awareness, but the concept still holds. Space collision avoidance will improve via the same self-imposed restraint when the proposed cooperation results in a clearer picture.

On 10 Feb 09, Iridium operators did not allow their spacecraft to collide intentionally with Cosmos-2251; those operators simply did not know Cosmos-2251 was

inbound to the same place as their spacecraft. Before and since the collision, Iridium operators have performed collision avoidance maneuvers based on the collective ability of the space community to predict spacecraft locations. The lack of knowledge that created the faulty internal policies and insufficient data that resulted in this collision can improve. With improved situational awareness data, planners and operators will improve the results of their existing software in order to meet the intent of the internal and external policies. In other words, improving the data used for orbit determinations will improve the collision avoidance results across the space community.

Continued success will require continued dialogue, much like the Soviet Union and U.S. diplomatic interaction during the Cold War. Game theory using the “prisoners’ dilemma” demonstrates significant improvement in collective results when participants communicate with each other during the game.¹⁴ Decision-makers should avoid nuclear war, like collisions in space, whenever possible. The same psychological factors influenced both Soviet and US nuclear activity during the Cold War, and the fact that the conflict remained “cold” is a testament to the ability of national leaders to address those factors with each other and within their own minds. History provides us with this example of fierce competitors who resolved daily conflicts without resorting to their most destructive capabilities.¹⁵

¹⁴ Steven Kull, *Minds at War* (New York: Basic Books, Inc., 1988), 20-21.

¹⁵ In his book written at the height of the Cold War, *Minds at War*, Steven Kull presents his extensive research into the psychology of nuclear war, including interviews with many Soviet, US, and European leaders while they were in power. Steven Kull, *Minds at War* (New York: Basic Books, Inc., 1988).

Leaders across the space community can learn from this example, accepting a small increase in the fear of each other in order to achieve a significant decrease in the fear of collision. Both sets of fears still exist, but rather than permitting those fears to paralyze leaders, the community should face those fears and determine reasonable ways to address the growing problem of collision with each other and existing debris. Creating additional unenforceable rules will not solve the problem, but overcoming fears to produce improved data through shared resources can result in true progress.

CONCLUSIONS

“Our way forward must involve a holistic and comprehensive view. We cannot afford to regard nation-states – or even regions, for that matter – as simple atomistic actors. Rather, they are interrelated, multi-faceted, and driven by any number of motivations and internal circumstances.”

—General Norton A. Schwartz, Chief of Staff, USAF¹

Successful efforts to overcome technical and psychological challenges will focus on reducing fear and building trust. Specific efforts may address a specific challenge, but collectively, each effort will contribute to improved collision avoidance. Transparency provides observable actions and dialogue that can contribute to both reduced fear and enhanced trust.

Fears are real, and one cannot discount them out of hand. However, if fear controls every move, even hiding in an underground bunker becomes insufficient as fear of enemy weapons penetrating even deeper overcomes any sense of security. In order to function in the world and in orbit, one must address fears realistically and prepare for reasonable risks. This preparation does not make the fear go away, but it does allow functional existence on Earth and in space. Technical solutions should address the concerns of each participant in order to gain that participant’s support.

Trust between competitors can exist regardless of whether or not they are allies. During the Cold War, NATO and the Warsaw Pact glared at each other across Europe, while the US and Soviet Union engaged in bloody proxy conflicts around the globe. This tense situation did not prevent countries on both sides of the divide from engaging in

¹ Norton A. Schwartz, “International Relationships: Toward a Twenty-First Century Security” Speech for International Fellows Program’s Alumni Dinner, October 1, 2009

meaningful diplomatic and economic transactions. In spite of the looming shadow of global thermonuclear war, competitors found ways to trust each other across a variety of topics. Military adversaries conducted the Strategic Arms Limitation Talks and signed the Strategic Arms Reduction Treaty based on a mutual desire to avoid physical destruction and to reduce the economic impact of maintaining excessive nuclear capability. Political rivals joined to create the United Nations and signed the Outer Space Treaty based on a mutual interest in increased prestige as peacemakers and enhanced presence from establishing a global stage. Economic competitors traded billions of dollars of goods and services and formed consortia together based on a mutual desire for increased profits and improved collaborative opportunities to develop new technology into viable products. Space includes many of the same entities, complete with all the same psychological challenges and similar opportunities for mutual benefit. While improving space collision avoidance is a complicated global challenge, the last 50 years offer several examples to consider for inspiration and caution.

Debris provides a common enemy, and all spacecraft owners and operators, military and civilian, have a stake in avoiding any intentional and unintentional collisions that would create more debris. With the proliferation of spacecraft today, debris creation has become the space version of Mutually Assured Destruction in global thermonuclear war, with no clear winner even for intentional collisions using ASAT weapons.

In light of the Chinese ASAT and past programs, spacecraft are vulnerable to attack.² Ambiguity about position cannot protect a spacecraft from a determined enemy with an ASAT, just as ambiguity about target location cannot prevent an enemy from using a nuclear weapon in every possible situation. In both cases, only the enemy can decide whether the consequences outweigh the benefits. From an idealist perspective, leaders should ban all weapons in space and should punish any attempt to develop such weapons. From a realist perspective, banning weapons is pointless, since a determined enemy will exploit any trust in such a ban as a weakness. For example, on September 11, 2001, terrorists exploited the US overreliance on trust in airline crew and passenger procedures and the belief that past terrorist activity to demand ransom or prisoner release would apply to all terrorists. The resulting tragedies stung the US people even more due to a sense of betrayed trust. Deviant intent is harder to identify than deviant behavior. As with aircraft, the space community should remain on guard, working to build trust, but acknowledging that a bona fide enemy can exploit blind trust.

Interdependence can create informed trust, especially to the extent that self-preservation precludes taking hostile action. The Soviet Union and the U.S. avoided nuclear war largely due to the expectation of retaliatory strikes and associated threats to an attacker's survival. While debris from ASAT tests or attacks threatens the survival of

² Salvatore Alfano, a respected astrodynamacist, provided an approach for determining the part of an orbit when a satellite is vulnerable to a direct ascent attack from a specific location, such as the location of the 2007 Chinese ASAT test. Salvatore Alfano, "Anti-Satellite Engagement Vulnerability" (Paper for an American Institute for Aeronautics and Astronautics conference, August 2009, available at: http://www.stk.com/downloads/support/productSupport/literature/pdfs/whitePapers/ASAT_EngagementVulnerability%20AAS%2009-415.pdf) (accessed May 19, 2010).

spacecraft along the trajectory of each piece, two factors are different. First, human life is not in jeopardy with remotely operated spacecraft, contrasted with nuclear explosions on population centers. Space debris affects quality of human life indirectly, but not life itself. Second, debris can last for centuries, while nuclear explosion effects dissipate faster. Hiroshima and Nagasaki are vibrant cities today, rebuilt soon after nuclear explosions over each city in the final days of World War II, but, as noted earlier, pieces of the Chinese Fengyun-1C will remain orbiting hazards well into the next century. Shared data and interdependent networks can inform participants of the hazards to their own spacecraft, serving to build cooperation toward trust while also serving as a reminder to any potential ASAT user of the long-term hazards that will remain for themselves and others long after a fateful decision. The resulting informed trust can serve as a counterbalance for speculative fear.

The larger effort should focus on avoiding unintentional collisions with improved sharing of raw data for orbital predictions being vital to this effort. External and internal policies and software will adjust to the availability of more, different, and continuous data. Since space operators already take great pains to maximize the lifespan of their spacecraft, very little encouragement is necessary to incorporate better source material into collision avoidance processes. Data availability is the only aspect that needs additional impetus.

Protection of intellectual capital will be critical to individual choices regarding data availability. For example, sensor designers desire to benefit from the fruits of their own research and labor. Given that it is possible to reverse engineer sensor data in certain cases in order to determine a specific sensor's operating parameters and

underlying technology, one must be careful not to confer unfair advantage to another sensor designer without consent from the originator. Sharing sensor data should include demonstrable guarantees regarding protection of the intellectual capital at stake. One possibility is to allow sensor operators to report calculated orbit predictions instead of raw data, but combined orbit predictions are generally less accurate than an orbit prediction combining the raw material. This reduced precision from combining orbit predictions could produce a larger covariance ellipsoid of position uncertainty. However, this option could be the only way a particular sensor operator will choose to participate, and orbital analysts can use additional software to minimize the effect on final orbit determination.³

Despite these efforts, suspicions will remain. Any robust process will include the opportunity for competitors to discuss those suspicions with common access to the relevant facts and the overriding goal of collectively avoiding collisions. Participation should include a mechanism for technical dialogue that can produce resolution in near-real time in order to support collision avoidance planning. Such dialogue would be more effective without public interaction, much like air traffic controllers handle pilots via radio with the understanding that all who speak on those frequencies are committed to safe aircraft movement at any given time. Any politically motivated interference in this real-time dialogue could be disastrous for spacecraft as well. This process should also include options for participants to speak privately, particularly if a participant has concerns about public perceptions. As with any private discussion, any public release of

³ Weeden and Kelso, “Analysis of the Technical Feasibility of Building an International Space Situational Awareness System,” 4.

material passed in confidence would destroy the associated trust. As long as mutual respect for each participant guides any discussion and outcomes, this process could resolve many suspicions.

Recommendations

In summary, the international space community has billions of dollars and innumerable vital data streams at risk from the growing collision avoidance threat. The preceding chapters and conclusions provide context and a framework for improving the current collision avoidance capabilities and processes that ultimately failed on 10 Feb 09. In order to protect their own assets as well as the rest of the space community, decision-makers should consider these recommendations for specific actions.

Focus on collision avoidance as a unifying issue. Beyond the first order risk of immediate loss in a collision, all other spacecraft owners lose access to many previously safe orbital options. In the remaining safe orbits, extra maneuvers to avoid debris expend fuel at a higher rate, shortening the mission lifespan of a spacecraft. Collisions in space create longlasting hazards, with the second and third order effects influencing orbits well into the next century. Decision-makers should periodically remind the space community of how improving collision avoidance lessens these effects at the source.

Recognize the role that emotions like fear play in personal behavior and collision avoidance. Leaders across the space community should be able to identify their own fears as a step toward addressing any emotional behaviors that seek to justify withholding cooperation despite the increased risks to their own interests. Emotions are part of being human, but effective leaders should combine those passions with rational decision-making aimed at improving collision avoidance.

Establish a non-military, apolitical international organization dedicated to continuous, effective collision avoidance for all spacecraft. These specific characteristics would address widely held fears about others weaponizing space and concerns regarding US global dominance. The organization could be based on international civil aviation or maritime organizations, adapted to include a 24-hour, real-time duty cycle like air traffic controllers. Workers in this organization must be technical experts in orbit determination who are able to concentrate on collision avoidance without additional agendas. Decision-makers should preserve the technical focus of this organization on day-to-day spacecraft maneuvers and should prevent others from co-opting its members or its products for negative political posturing.

Encourage participation from all spacecraft and sensor owners and operators. National military and civilian organizations, international corporations, academic institutions, amateur astronomers and many others can contribute greatly to mutual success. Because the primary goal of this cooperative effort is collision avoidance, it is imperative not to exclude any member of the space community willing to contribute tangibly to improving collision avoidance. As witnessed during the Cold War, technical dialogue between enemies/competitors can provide a forum to address fears and suspicions with facts and positive actions. Decision-makers should publicize initial improvements from early cooperation in order to convince skeptics of the benefits from involvement.

Decide the level of liability for this organization. One liability option is to make collision avoidance messages advisory only, meaning recipients are not obligated to regard them as direction. This protects the organization from a liability standpoint, but

does little to encourage participation. Another option is to make this organization completely responsible for consequences resulting from its output – if recipients adhere to collision avoidance guidance from this organization, then the organization becomes directly responsible for any resulting collisions. This choice adds a heightened sense of urgency across the community to provide the information needed for high quality guidance in order to reduce risk of collision and reduce unnecessary life-limiting maneuvers. As a result, decision-makers should agree to assign the organization the highest level of liability possible.

Determine acquisition and development concepts. The organization will need equipment and software to address technical challenges with data sharing. Based on ability, decision-makers should consider accepting financial and functional responsibility for specific components from development to disposal, with accountability to the collective organization for the success or failure of those components.

Match participants with proportional long-term funding responsibility. Participants with the most spacecraft should supply the most resources, since their spacecraft will consume the most collision avoidance time and effort. Previous international space efforts have shown better long-term results from providing personnel or equipment rather than cash. Centralized funding requires more bureaucracy to provide the necessary oversight, and this bureaucracy will require its own funding, adding expense for questionable benefit. In contrast, decision-makers should determine internal funding streams for the specific components under their responsibility, answering to the organization for providing the associated personnel, information, and/or materiel.

Establish an internal process to resolve conflicts in near-real time. Debris cannot move, so all spacecraft must avoid debris. When predictions indicate a conjunction between two active spacecraft, this organization should have clearly understood methods to determine which spacecraft will yield. Current UN efforts to establish “rules of the road” may help, but actual circumstances often do not fit neatly into a given list of rules. One spacecraft owner may lose a one-time opportunity for research or may be nearing end-of-life fuel levels, where the other spacecraft may have more flexibility, despite having the “right-of-way.” This organization will need an internal process for swift consultation with multiple operators to resolve conflicting priorities on a technical basis without emotional or political grandstanding. Based on the response to the earlier liability question, the organization should have much incentive to make the right calls. This recommendation adds the requirement that decision-makers enable and empower the organization to resolve real-time conflicts on a technical basis. Participant operators would welcome this opportunity to state their technical needs such as fuel and mission requirements, especially if the organization’s standard response in accordance with a list of rules would penalize a participant unnecessarily.

Establish a method to deconflict sensor tasking across the larger network. Current sensors have various methods for searching, tracking, and reporting on space objects in response to demands from their current independent network. Linking networks and additional sensors together will require forethought to preclude all sensors from tracking one set of objects exclusively, leaving other objects unobserved for weeks or months. Similar to current networks, decision-makers in this expanded international network

should agree on a framework for optimizing all available sensors for both standard and unique situations.

On a related note, when the organization is able to ingest reliable spacecraft-reported positions (e.g., GPS-based location), sensors can devote more attention to debris or spacecraft not willing or able to report their positions. For any spacecraft whose owners attempt to hide their position for whatever reason, this organization should not attempt to “out” them for political benefit, since that attempt would not fall within its intentionally limited collision avoidance charter. All observation efforts of such a spacecraft should remain focused on collision avoidance only, constantly handing off observation of the spacecraft between sensors in order to maintain safe separation for all others. This organization must remain focused solely on maintaining effective situational awareness that leads to safe access to space for all participants.

Determine how to protect intellectual capital of each participant. Participation in this organization cannot equal giving technical advantage to competitors. As a result, this organization should have stringent safeguards in place to protect participants’ technical specifications, even from other participants. Otherwise, some owners may want to add uncertainty into their reports in order to protect a real or perceived advantage. Since the collective goal is to produce more accurate orbit predictions to improve collision avoidance, the less accurate data may be better than no data until an acceptable protection mechanism is in place. Decision-makers should protect each participant’s intellectual capital, including from other participants, respecting existing advantages. Remain focused on collision avoidance in space, not on relative advantages among participants.

The time for consensus is now. Every member of the space community needs to recognize that the long-term debris hazards from two recent events, the deliberate Chinese ASAT test and the unintentional Iridium-Cosmos collision, have made the risk of collision large enough for all users to seek ways to overcome arguments against real cooperation. In contrast to catalog maintenance, effective space traffic management requires pooling of international resources. Decision-makers who support the recommendations above will establish an international capability to utilize any UN-generated “rules of the road” successfully, a capability that does not exist today. Developing collective responsibility will lead to sustained collective success. Closer teamwork on Earth will result in better separation in space.

APPENDIX A: RECOMMENDATION LIST

The international space community has billions of dollars and innumerable vital data streams at risk from the growing collision avoidance threat. Here are 10 recommendations decision-makers should consider in order to protect their own assets:

1. Focus on collision avoidance as a unifying issue.
2. Recognize role of emotions like fear in personal behavior and collision avoidance.
3. Establish non-military, apolitical, international organization dedicated solely to continuous, effective collision avoidance for all spacecraft.
4. Encourage participation from all spacecraft and sensor owners and operators.
5. Decide level of liability for the organization.
6. Determine acquisition and development concepts.
7. Match participants with proportional long-term funding responsibility.
8. Establish internal process to address conflicts between participants in near-real time.
9. Establish method to deconflict sensor tasking across the larger network.
10. Determine how to protect intellectual capital of each participant.

Closer teamwork on Earth will result in better separation in space.

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